WORKING PAPER 51

A Preliminary Discussion of Karst Inventory Systems and Principles (KISP) for British Columbia

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A Preliminary Discussion of Karst Inventory Systems and Principles (KISP) for British Columbia

T.R. Stokes and P. Griffiths

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The primary purpose of the preliminary KISP document is to provide an initial scientific framework within which improvements and refinements can be made. It is recommended that users not rigidly apply the preliminary KISP methodologies outlined in the document, but rather use their experience and judgement to adapt them to their own needs. Feedback from users will be critical for the completion of the KISP. Comments and discussion on the concepts within this document are both anticipated and needed to ensure that the final KISP methodologies are both technically sound and feasible.

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SUMMARY

The need for a standardized karst inventory system has developed from issues related to the sound management of forested karst areas. Previous management practices focused on caves and individual karst features. Our basic aim in producing this document is to assess karst as a functional ecosystem, considering all its non-living physical and chemical attributes (e.g., distinct geological, geomorphological, and hydrological features) and its associated living flora and fauna.

The preliminary Karst Inventory Systems and Principles (KISP) document reviews the current status of karst inventory methodologies in British Columbia and proposes a set of standard methodologies for karst inventories at the reconnaissance (1:250 000 scale), planning (1:50 000 and 1:20 000 scales), and operational (1:10 000 and 1:5000 scales) levels. A methodology for karst ecosystem vulnerability assessment is also proposed, and is directly linked to the planning- and operational-level karst inventories.

The reconnaissance-level inventory is an office-based assessment that utilizes existing bedrock geological maps, known bedrock lithology data, and any available karst information. A series of criteria is developed at this level to rate geological units for their likelihood of containing karst-forming bedrock, the intensity of karst development, and the known presence of caves or major surface karst features.

The planning-level inventory utilizes a phased approach to assess karst units. Phase 1, or the upper-level planning, combines detailed office work and reconnaissance field work to check the surface boundaries of karst units and collect basic geological and geomorphological information (e.g., bedrock lithology, major folds and faults, large surface or hydrological karst features). Phase 2, a karst-modified terrain mapping methodology, is carried out on large and/or complex karst areas to stratify polygons with varying intensities of karst development. These polygons can then be rated using a vulnerability assessment methodology, and, in combination with information on proposed activities and adjacent resources (e.g., fish habitats), assist in forest management planning. Phase 3, regional dye tracing, should be used when it is apparent that significant karst hydrological features are present or when subsurface flow paths are not reliably inferred from existing information. Dye tracing assists in delineating recharge areas and in determining subsurface flow paths.

The operational-level inventory is carried out by detailed field work that locates, identifies, and classifies surface karst features (e.g., sinkholes) and cave entrances. Subsurface inspection and classification of caves systems are carried out in some cases. The operational inventory can lead to other specialized inventories; for example, karst fauna (e.g., bats), karst flora (e.g., calcophile plants), and subsurface resources (e.g., paleontological, archaeological). The operational inventory report can, in some cases, be used to provide recommendations for management prescriptions or mitigative measures (e.g., buffers along sinking streams).

The operational-level inventory is linked to the vulnerability assessment methodology, within which the four basic environmental states of the karst ecosystem (air, water, land, and biota) are qualitatively

assessed. The highest rating obtained from the four environmental states is then used to provide an overall vulnerability rating. The operational vulnerability rating can be used in combination with details on proposed forest activities (e.g., harvesting or road construction) and adjacent resources (e.g., downstream fisheries) to carry out risk assessments for karst areas.

Further testing and discussion of the karst inventory and vulnerability methodologies is anticipated and warranted, particularly for the planning-level inventory and for the vulnerability assessment procedures.

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1.1 Purpose, Approach, and Limitations

The aim of this document is to provide the following in a straightforward manner:

- a set of common procedures for completing karst inventories in British Columbia,
- a scientific framework within which data collection, analysis, and presentation of karst inventory information can be carried out, and
- a tool to assist workers in completing inventories, agencies in reviewing inventories, and land-use managers in making decisions.

The terms of reference for the project were developed in a proposal submitted to the British Columbia Ministry of Forests on November 27, 1997. The terms of reference are as follows:

- To complete an overview of current karst inventory activities in British Columbia, and to review a selection of karst inventory reports completed for the B.C. Ministry of Forests, the British Columbia forest industry, and other agencies outside British Columbia.
- To develop preliminary karst inventory procedures (KISP) at operational, planning, and reconnaissance levels for eventual approval by the Resources Inventory Committee (RIC).
- To develop a methodology for evaluating karst vulnerability, and evaluate the potential linkages with the different levels of inventories in the KISP.
- To evaluate the proposed KISP in terms of conformity and cross-linkages with other existing RIC inventories.
- To produce a final report summarizing the findings and limitations of the work completed, with suggestions for further work.

It should be understood that the preliminary KISP document was constrained by a number of critical factors:

- The short time period available for the project (December 15, 1997 to March 31, 1998).
- The limited technical review of the document from other specialists.
- The lack of any existing karst-specific guidelines for inventories or forest management in British Columbia.
- The limited areas within British Columbia where karst inventories have been carried out.
- The lack of systematic research into the processes of forested karst ecosystems within British Columbia.

This document provides proposed procedures for completing reconnaissance-level (1:250 000), planning-level (1:50 000 to 1:20 000), and operational-level (1:10 000 to 1:5000) karst inventories. The highest karst inventory level (reconnaissance) begins at the regional scale, and the inventory process focuses in progressively through an intermediate

(planning) scale to a more detailed (operational) scale, with an increasing requirement for karst attribute[1] data collection and evaluation.

A fundamental characteristic of karst terrain is its three-dimensional nature. This is primarily the result of high bedrock solubility and well-developed secondary (fracture) porosity, which produces distinctive surface and subsurface features. The primary control on this process is the hydrological cycle, which involves surface and subsurface interactions between water and bedrock. These processes are slow but, over time, lead to unique geomorphological, hydrological, and ecological attributes.

The fundamental concept underlying the proposed karst inventory methodologies is that karst should be considered a system, as opposed to a collection of discrete surface features that may or may not be connected to subsurface openings or caves[2]. Caves are one of the "focal points" of karst, and have been the past focus of karst inventories in British Columbia. However, they typically make up only a very small (e.g., 0.01%) portion of a typical karst unit. The system approach recognizes that karst operates as one holistic unit, whereby changes to conditions at the land surface can influence conditions below (e.g., heavy rainfall at the surface can lead to subsurface flooding). The connectivity or openness of a karst system is the critical factor that controls the changes to the system and the speed with which these changes occur. The aim of the inventory methodology outlined in this document is to focus not only on the basic karst system (with its distinct geological, geomorphological, and hydrological attributes), but to examine the karst system in a holistic manner as an ecosystem. A karst ecosystem can be defined as a functional unit consisting of all living and non-living physical and chemical elements of the karst environment that are linked through nutrient cycling and energy flow.

Globally, carbonate karst terrain itself is not unique, and is exposed on approximately 7–10% of the earth's land surface (Ford and Williams 1989). It is suggested that inventories and management of karst should be considered no less or more important than non-karst terrain, as both can hold valuable, though different, resources. Nevertheless, it is well recognized that karst terrain is potentially very sensitive to natural and human-made changes (Kiernan 1990; Harding and Ford 1993; White et al. 1995). With this in mind, it should be recognized that karst terrains and ecosystems warrant karst-specific inventories because of their fundamental differences in geomorphology, hydrology, and ecology.

1.2 Karst Processes with Particular Reference to British Columbia

This document focuses on karst derived from carbonate bedrock (e.g., limestone, dolomite). Non-carbonate bedrock types, such as evaporites (gypsum, anhydrite, and salt), can also develop karst features, but they are limited in their occurrence in British Columbia. The development of karst terrain (i.e., karstification) depends on the interaction of at least eight controlling factors: bedrock lithology, hydrogeology, bedrock structures, topography, climate, vegetation cover, time, and glacial history.

[1] A karst attribute is any feature of karst, non-living or living, that is specifically dependent on a characteristic of the karst ecosystem or process, and can range from sinkholes and springs to bats and subsurface air.

[2] The B.C. Ministry of Forests defines a cave as a "cavity in the earth which connects with the surface, contains a zone of total darkness and is large enough to admit a human being".

Carbonate bedrock is primarily susceptible to karstification because of its solubility. Typically, the best karst occurs in limestone with greater than 70% $CaCO_3$ (Ford and Williams 1989). Generally, the purer the limestone, the better the development of karst. Carbonates, of variable composition, make up approximately 10% of the landscape surface of British Columbia (Fischl 1992). Of this, approximately one-fifth is dolomite, while the rest is limestone. In addition to the composition of carbonates, the thickness of individual beds and the nature of interbeds can affect the degree of karstification (Sweeting 1973). In certain lithologies in British Columbia, the depth of surface karstification is limited by impermeable beds (Sweeting 1973).

The solution chemistry of carbonate rocks is reasonably well understood. Dissolution of limestone, for example, involves carbon dioxide, water, and calcium carbonate. Atmospheric carbon dioxide diffuses into water within the air or soil, where it is hydrated to form carbonic acid. The carbonic acid dissolves the limestone. Only water under-saturated with respect to dissolved carbonate is capable of dissolving limestone. The time required for this aggressive water to be neutralized or to reach saturation equilibrium varies from minutes to hours. The duration depends on a number of factors including temperature, dilution, turbulence, partial pressure of carbon dioxide, presence of other acids, and surface area of subject rock. Dissolution rates can fluctuate with precipitation events that can flood the karst surface and subsurface cavities with under-saturated water. Once the saturation equilibrium is achieved, warmer water temperatures or a decrease in the partial pressure of carbon dioxide can result in the deposition of calcium carbonate. Organic acids from vegetation and soils also contribute to the dissolution process (Viles 1988). The karstification process involves not only the dissolution of carbonate, but also significant mechanical erosion processes.

The depth to the water table in a karst network can vary widely in space and time due to high permeability and intermittent flooding. Networks can be heterogeneous free-flow systems with enlarged open conduits. Erosion rates for karst can vary even within the same climatic zone.

Tectonic movements, which can uplift or deform a carbonate unit, have a regional influence on the rates and degree of karstification. Bedrock structures, such as folds and faults, are a common result of tectonic movements. Typically, with uplift, a karst unit becomes more fractured, can have increased hydraulic gradients, and may be subjected to greater precipitation (e.g., Vancouver Island and the Coast Mountains). These combined influences can lead to the development of solution-enlarged conduits along fracture planes and accelerated dissolution. This is the fundamental process that leads to the three-dimensional nature of karst. At the smaller scale, vertical fractures at the surface are important for focusing water flow along them, while folding and faulting can isolate karst units and redirect groundwater flow.

Typically, in British Columbia, the higher the elevation, the greater the abundance of karst features (e.g., along the Rocky Mountains [Rollins 1992]). Higher topographic relief leads to greater differences in hydraulic head, with the water table sometimes occurring hundreds of metres below the land surface. This, in turn, leads to the development of a more extensive

and efficient subsurface drainage system characterized by steeper hydraulic gradients and high subsurface flow rates.

The climate of British Columbia is conducive to karstification. Some of the best-developed karst is found in the humid coastal and high mountainous regions, where solutional erosion rates can be particularly intense due to greater rainfall and carbon dioxide production in soils. The higher the carbon dioxide absorption in water, the greater the chemical aggression of the infiltrating water.

Vegetation cover influences the generation of biogenic carbon dioxide in the soil through plant root systems and bacterial decay. The partial pressure of carbon dioxide in soil air is often 10–100 times greater than that of the atmosphere (Jennings 1971). As a consequence, the presence and nature of soil cover can play a very significant role in the karstification process. With higher biogenic activity, higher rates of carbon dioxide production occur. The densely forested areas of Vancouver Island, for example, frequently support an intensified level of surface and subsurface karstification (Harding and Ford 1993). Where forest productivity is greatest, there also tends to be increased moisture and free water circulation. These conditions can also lead to higher solution erosion rates. More sparsely vegetated, thinly soiled, and arid areas of the province are expected to have a slower rate of surface karstification.

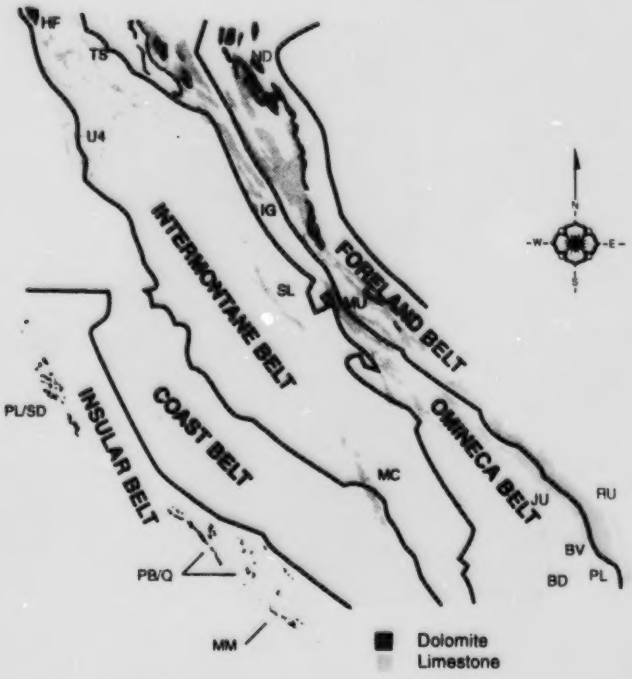
Glaciation has played an important role in the destruction, preservation, and development of karst. Almost all of the British Columbia landscape, except for the highest mountain peaks, has undergone glaciation in the geological past. Erasure of shallow karst features and zones can be carried out by glacial abrasion and plucking. In many places, provided openings are large enough, karst features can be either shallowly infilled or deeply injected with glacial debris. The Nakimu Caves in southeast British Columbia have conduits filled to a depth of 120 m during the last glacial event (Ford 1987). Glaciation can also shield or seal terrain from erosion by either depositing thick layers of glacial debris, which lowers the activity of karst-forming solutions, or by the action of sheets of flowing ice that reduce the abrasion effects. One of the major glacial effects occurs during glacial recession, when meltwaters are focused or deeply injected into karst aquifers. This can result in extensive shaft formation, the collapse of existing karst formations, and the redirection of subsurface flows.

The geological ages of karst formation in British Columbia are not well documented, but, in many cases, they predate the last period of glaciation, which ended approximately 10 000 years ago. In numerous areas, it is apparent that various episodes of karst formation have been superimposed on one another. Karst systems in the Castleguard area of the southern Rockies are reported to be at least 750 000 years old (Trenhaile 1990). On Vancouver Island, U-series dates of 28 000 and 64 000 years old were obtained from speleothem material (Gascoyne et al. 1981). From speleothem dates and glacial till deposits in cave passages, it has been suggested that parts of the White Ridge cave system formed pre-deglaciation, approximately 13 000 years ago (Ecock 1984). More recent carbon dating of marmot and bear bones from caves on Vancouver Island have also provided age constraints on their formation (Hebda 1995). Paleokarst (karst of considerable geological age and not related to present geomorphic conditions) also likely occurs within the carbonate units of

British Columbia (e.g., it is part of the mineral replacement process for many ore deposits). Thus, the timing of the karstification process can be considered complex, and it is difficult to determine whether karst development within a carbonate unit is thousands, hundreds of thousands, or millions of years old.

1.3 Distribution of Karst in British Columbia

As previously noted, extensive areas of carbonate bedrock are present across British Columbia (Figure 1). In terms of distribution, most of this soluble rock (made up of both dolomite and limestone) occurs as extensive belts along the Rocky Mountains and forms part of the Foreland Tectonic Belt (Table 1). Smaller, but continuous, limestone belts occur in the Purcell Mountains (Kootenay Arc), at the southern end of the Interior Plateau, east of Takla Lake, in the Cassiar Mountains, and on Vancouver Island. Other smaller limestone occurrences are found in scattered bodies along the west coast, along the U.S. border (at Chilliwack, Greenwood, and Trail), on the east coast of the Queen Charlotte Islands, and in the North Okanagan.



Note: This is not a karst map, but indicates only the known extent of most carbonate units in British Columbia.
Refer to Table 1 for unit abbreviations.

FIGURE 1 *Tectonic belts of British Columbia (adapted from Figure 1 and Map 1 of Fischl 1992).*

All six forest regions of British Columbia are underlain by varying amounts of carbonate bedrock (Figure 2). The extent of karst development within the carbonate bedrock units, and the ecological relationships with the associated forests, are not well known. Strategic-level (1:250 000 scale) karst inventories have been carried out for the Vancouver and Prince Rupert Forest Regions (see Section 3.0). The distribution of carbonate rocks and the current knowledge of karst, particularly with respect to forested areas, are summarized below for each of the forest regions.[3]

[3] The information provided is based on the current knowledge of the authors and could likely be improved by input from local geologists, cavers, and others.

FIGURE 2 *Forest regions of British Columbia.*

TABLE 1 *Principal limestone and dolomite units in British Columbia (taken from Fischl 1992). (Note: likely minor units in italics.)*

Abbreviation	Name of unit	Regional location	Unit description	Dimensions/Structure	Age
	INSULAR BELT				
PB	Parson Bay Fomation	Vancouver Island	Interbedded argillite, calcareous siltstone/ sandstone, limestone	Stratigraphically above Quatsino Formation	Triassic
Q	Quatsino Formation	Vancouver Island	Massive to thick bedded limestone	Three belts in north of island 30–165 km long, steeply dipping and segmented by faults	Triassic
MM	Mount Mark Formation	Vancouver Island	Massive to thick bedded limestone	Up to 360 m thick	Early Permian to Late Pennsylvanian
PL	Peril Formation	Queen Charlottes	Thinly bedded black limestone	Intensely faulted and folded	Triassic
SD	Sadler Formation	Queen Charlottes (Moresby Island)	Massive grey limestone	<30–180 m thick, NW-trending belts	Triassic
	COAST BELT				
U1	*Unknown surrounded by granitic bodies*	*Distributed along west coast of B.C. mainland*	*Recrystallized, limestone/marble, some dolomitized*	*Small bodies 10s–100s m wide and 100s–1000s m long*	*Triassic in south of belt*
	INTERMONTANE BELT				
CL	Chilliwack Group	Fraser Valley, Chilliwack	Two distinct limestone units in sequence of argillite, siltstone, sandstone, chert, and pyroclastics	Lower unit 30 m thick, upper unit 60–90 m; locally up to 600 m, faulted and folded	Lower Pennsylvanian to Lower Permian
MC	Marble Canyon Formation (Cache Creek Group)	Belt extending from Cache Creek to Williams Lake	Massive to well-bedded limestone (interbedded with argillite, chert, and mafic volcanics of Cache Creek Group)	Up to 100s m thick, extends for 175–250 km, faulted and folded	Middle to Upper Permian
SL	Stuart Lake Belt (Cache Creek Group)	250 km belt extending from Vanderhoof to Omineca River	Massive blue-grey limestone, dolomitic in places	460–3000 m wide	Pennsylvanian to Permian
HF	Horsefeed Formation (Cache Creek Group)	Part of 400 km belt from Tagish Lake to Stikine River	Massive pale grey to buff-grey fossiliferous limestone	900–1500 m wide, moderately folded and faulted	Late Mississippian to late Permian
TS	Telsin Formation (Cache Creek Group)	Part of 400 km belt from Tagish Lake to Stikine River	Massive, fine-grained, dark grey to black limestone	<300–600 m wide in sporadic areas	Permian

TABLE 1 *(Continued)*

Abbreviation	Name of unit	Regional location	Unit description	Dimensions/Structure	Age
KD	*Kedahda Formation (Cache Creek Group)*	*Part of 400 km belt from Tagish Lake to Stikine River*	*Chert and argillite with minor lenses of volcanics and carbonates*	*Pods 800 m long and 100 m thick or beds 30 m thick*	*Mississippian and Early Permian*
HR	*Harper Ranch Group*	*Discontinuous for 150 km from Vernon to Hedley*	*Sequence of argillite, sandstone, conglomerate, chert, volcanic flows, and limestone lenses*	*Variable in size and distribution, up to 3 km in length*	*Mississippian to Late Permian*
U2	*Unnamed Permian Limestones*	*Terrace Area, Babine Lake and Stikine River*	*At Terrace, limestone associated with volcanic and meta-sediments; others as small limestone bodies*	*At Terrace, bodies 30–120 m thick and up to 3 km long; others as small isolated bodies*	*Permian*
HZ	*Hozameen Group*	*Fraser River to U.S. border*	*Sequence of argillite, chert, mafic volcanic, and minor limestone*	*Typically <30 m thick, but up to 300 m recorded*	*Permian to Lower Jurassic*
FG	*Fergusson Group*	*Near Gold Bridge*	*Sequence of chert, argillite, phyllite, basalt, andesite, and limestone lenses*	*Typically 15 m thick, but can be up to 90 m thick and 300–900 m long*	*Permian to Middle Jurassic*
NC	*Nicola Group*	*Three belts between Fraser River and Okanagan Lake*	*Sequence of felsic to mafic flows, sediments and volcaniclastics with sporadic lenses and beds of limestone*	*Isolated bodies and lenses 30–300 m thick and up to 4 km long*	*Middle to Upper Triassic*
SH	*Shoemaker Formation*	*Keremeos*	*Silicified volcanics, tuff, and breccias with minor fossiliferous limestone*	*Isolated bodies 60 m wide and 150 m long*	*Upper Triassic*
TA	*Takla Group*	*Babine Lake and Beverley*	*Andesite, basalt, tuff, and breccia with minor conglomerate, shale, and limestone*	*Small lenses <500 m by 1000 m in area*	*Upper Triassic*
	OMINECA BELT				
IG	**Ingenika Group (Espee Formation)**	**300 km belt from Manson River to Turnagain River**	**Thick interbedded sequence of phyllite, schist, quartzite, and limestone (more dolomitic to the north)**	**Thickness of unit varies from 150 to 1000 m wide, mainly confined to Espee Formation**	**Precambrain (Hydrynian)**
LA	**Laib Formation**	**Three belts near Salmo 40 km long**	**A succession of phyllite, schist, quartzite, and limestone**	**Discontinuous bands displaced by faulting and folding**	**Lower Cambrian**

TABLE 1 *(Continued)*

Abbreviation	Name of unit	Regional location	Unit description	Dimensions/Structure	Age
BD	Badshot Formation	Occurs in a broad arc for 250 km from south of Nelson to north of Revelstoke	Combination of massive to banded recrystallized limestone and white to black dolomite	Outcrops as a series of bands, thinned and thickened by folding 6–100s m thick	Lower Cambrian
TS	Tshinakin Limestone	20 km band in Adams Lake region	Massive fine-grained limestone, dolomitic in areas	Locally up to 1000 m thick	Lower Cambrian
MU	Mural Formation	100 km belt from Purden to Bowron Lakes; mainly oolitic limestone and some dolomite	Two carbonate units separated by a shale	Varies in thickness from 150 to 750 m	Lower Cambrian
ML-CR	McLeod Lake - Crooked River	300 km belt from McLeod Lake to Herrick Creek	Dolomite and limestone with interbedded sandstone, quartzite, shale and siltstone	80–100 m wide near Tacheeda Lake	Lower Cambrian
NL	Nelway Formation	Two irregular belts from U.S. border to South Salmo River	Three member units of dolomite and limestone	4 and 9 km belts 1350–1500 m thick	Middle Cambrian
LR	*Lardeau Formation*	*South of Nelson to north of Revelstoke, and Trout Lake area*	*Overlies Badshot Formation, sequence of gneiss, schist, quartzite, amphibolite, and minor limestone (marble)*	*<1 m to 30 m thick at base of formation, dolomitized in places*	*Middle Cambrian to possible Mississippian*
SP	Sandpile Group	Several scale belts in the McLeod Lake area	Silty dolomite and limestone with some interbedded sediments	Up to 360 m thick	Middle Silurian
PO	*Pend d'Oreille Sequence*	*Pend d'Oreille at U.S. border*	*Thick sequence of phyllite, argillite, quartzite, chert, greenstone, and limestone*	*120–900 m wide, 8 km long*	*Silurian (?) to Carboniferous*
AN	*Anarchist Group*	*Greenwood - U.S. border*	*Sequence of schist, quartzite, chert, greenstone, limestone, and amphibolite*	*Isolated lenses and beds up to 90 m thick and 50 m to 3 km long*	*Carboniferous*
MI	*Milford Group*	*Discontinuous belt from Kootenay Lake to Upper Arrow Lake*	*Sequence of argillite, slate, schist, and quartzite with minor chert, greenstone, limestone, and dolomite*	*Beds and lenses up to 120 m thick*	*Mississippian*

TABLE 1 *(Continued)*

Abbreviation	Name of unit	Regional location	Unit description	Dimensions/Structure	Age
SM	*Slide Mountain Group*	*270 km belt from Williston Lake to Barkerville*	*Belts of basaltic flows, pyroclastics, argillite, slate, chert, sandstone, and limestone*	*Significant body on west side of McLeod Lake*	*Mississippian to Triassic*
KH	*Knob Hill Group*	*Greenwood area*	*Massive chert, argillite, greenstone, and amphibolite with limestone pods*	*Small pods 100s m in dimensions*	*Carboniferous or Permian*
MR	*Mount Roberts Formation*	*Several belts near Christina Lake, one up to 30 km long*	*Schist, slate, graywacke, greenstone, limestone, and gneiss*	*27–240 m thick limestone bed 3–8 km long*	*Pennsylvanian or possibly Permian*
SI	*Sicamous Formation*	*Irregular 30 km belt near Sicamous*	*Two limestone beds separated by a sericite schist*	*Limestone bodies up to 2.5 km wide and 6 km long*	*Middle to Lower Mesozoic ?*
BR	*Brooklyn Formation*	*Greenwood area*	*Lower, conglomerate and siltstone member; upper, limestone member*	*Sporadic, lenticular masses up to 800 m wide and 4 km long*	*Middle Triassic*
MC	*Metamorphic Complexes*	*Okanagan and Kootenay Lakes to south Adams Lake and Columbia River to north*	*Carbonate beds/ pods in schists and gneisses*	*Isolated pods of recrystallized limestone and dolomite*	*Unknown*
	FORELAND BELT				
JU	Jubilee Formation	150 km belt from Wasa to Harrowgate	Thickly bedded to massive dolomite	120–1200 m wide	Middle to Upper Cambrian
BV	Beaverfoot Formation	In south, 200 km belt from Wasa to Golden; in north, 120 km from Herrick to Anzac Creek	Thickly bedded to massive dolomite	Variable width from 7 to 600 m	Upper Ordovician
ND	Nonda Formation	600–650 km belt from McGregor River to Yukon	Mainly dolomite, but with a very pure limestone member	100–1000s m wide	Lower Silurian
PL	Palliser Formation	In south, two belts up to 140 km and 170 km long (Fernie to Palliser River); in north, 120 km from Forgetmenot Creek to Quintette Mt.	In south, the unit is comprised of a massive and nodular limestone with some dolomite; in north, massive to thick bedded micritic limestone	Widths 50–200 m recorded	Upper Devonian

TABLE 1 *(Concluded)*

Abbreviation	Name of unit	Regional location	Unit description	Dimensions/Structure	Age
RU	Rundle Group	Outcrops as km to 10s km belts discontinuously along most of the Canadian Rockies	Mainly limestone with more argillaceous and dolomitic material in upper sections	Typically 100–300 m wide	Mississippian
SF	*Unknown Southern Foreland Belt*	*Isolated bodies near Wardner*	*Limestone and dolomite*	*Small isolated bodies 10s to 100s m in dimensions*	*Unknown*
NF	*Unknown Northern Foreland Belt*	*Isolated bodies near Sukunka River*	*Limestone*	*10s m wide and few 100s m long*	*Unknown*

1.3.1 Vancouver Forest Region

Most of the best-known forested karst areas of British Columbia occur in the Vancouver Forest Region on Vancouver Island. The principal karst-forming units are the Quatsino and Mount Mark formations, which occur as massive, moderate to steeply (20–50%) dipping limestone belts, segmented by faults and intruded by granitic bodies. The Parson Bay Formation is stratigraphically above the Quatsino Formation and is comprised of inter-bedded argillite, calcareous siltstone/sandstone, and grey/black limestone. A variety of karst types is encountered on Vancouver Island, including:

- alpine-type karst with little to no surficial/vegetation cover and intensely developed epikarstic pavements (e.g., White Ridge, Clayoquot),
- plateau-type karst occurring on broad, elevated ridges with variable soil thickness and tree cover (e.g., Artlish River, Tashish River),
- valley-bottom karst with thick glacial cover (e.g., Benson River, San Josef River),
- mid-slope and upper-slope karst with a range of surficial cover thickness (e.g., east of Nimpkish Lake), and
- shoreline-type karst (e.g., Texada Island, Nootka Island).

The Kunga Group on the Queen Charlotte Islands is composed of two limestone formations, the Peril and the Sadler, which mainly occur in the north and southeast of Moresby Island. Karst development within these formations is not well known. However, some minor cave areas have been reported locally.

Forested karst areas are also known to occur in the Chilliwack region associated with the Chilliwack Group. This group is comprised of two limestone units in a sequence of argillite, siltstone, sandstone, chert, and pyroclastic rocks. Numerous cave and karst areas have been identified in the region.

Small (10s–100s metres wide and 100s–1000s metres long) isolated bodies surrounded by granitic intrusives occur along the southwest mainland coast of British Columbia, from Howe Sound to Milbanke Sound. Most of the carbonate units are intensely metamorphosed, dolomitized, and recrystallized.

1.3.2 Prince Rupert Forest Region

In the southern part of the Prince Rupert Forest Region, small limestone bodies occur along the coastline, near Terrace, and around Babine Lake. Caves and karst within the coastal forested areas have been reported only in a few cases (e.g., Chapple Inlet on Princess Royal Island). In the northern part of the region, most of the limestone and dolomite areas occur in major belts that extend along the Cassiar Mountain Range, much of which is in alpine or subalpine settings. Along the border with Alaska, some limestone areas occur close to coastal rainforest and subalpine forests (Figure 3). Reports of karst development in the region are limited, but include sinkholes along the Stikine River and stream resurgences in the Sinwa Formation along the Taku River.

1.3.3 Cariboo Forest Region

Two belts of carbonate rock are present within the Cariboo Forest Region, one south of Williams Lake, the other to the east of Quesnel in the Quesnel Highlands. The belt to the south of Williams Lake occurs within the massive to well-bedded limestone of the Marble Canyon Formation, while the other area occurs within the limestone of the Mural Formation. Karst development and associated solution features have been reported in the Marble Canyon Formation within the Pavilion Range.

1.3.4 Prince George Forest Region

Extensive areas of limestone and dolomite are present within the Prince George Forest Region along the Rocky Mountains to the northeast of Williston Lake. Much of the carbonate occurs within alpine and subalpine areas; the latter is commonly forested in the south of the region. Other major belts of limestone and dolomite are found along Takla Lake and in the Hart Ranges, northeast of McLeod Lake. Most of these carbonates occur within forested subalpine settings. Karst and caves have been reported in many areas within the region including the Dezaiko, McGregor Range, Mount Bocock, and the Bastille areas (Rollins 1997). A karst inventory related to forestry activities has also been carried out in the Herrick Creek Watershed (Interior Karst Consultants Ltd. 1997).

1.3.5 Nelson Forest Region

A major belt of carbonate occurs in the west of the region along the southern end of the Rocky Mountains and the border with Alberta, much within alpine or subalpine settings. Extensive areas of karst and cave systems have been identified (e.g., the Castleguard Cave System, which occurs mainly in Alberta). A narrower belt of limestone, mainly composed of the Badshot Formation, extends north–south through the centre of the region from Nelson to northeast of Revelstoke. This belt extends through forested interior, subalpine, and alpine settings. At one location near the Cody Caves Provincial Park, forested areas are known to occur on karst. Other areas with concentrations of small limestone bodies/belts occur near Greenwood and Trail. Gypsum-related karst is known near Canal Flats.

1.3.6 Kamloops Forest Region

The southern end of the Marble Canyon Formation extends into the northwest corner of the region west of Kamloops. A smaller belt of limestone occurs in the Adams Lake area to the northeast of Kamloops. Other scattered bodies of limestone occur throughout the region and, in many cases, appear as beds or lenses with thick sequences of volcanic and sedimentary rocks. Some of these limestone areas occur within forested interior settings. No reports of cave or karst features are known.

Carbonate-bearing units adapted from Fischl, P., *Limestone and Dolomite Resources in British Columbia*, Open File 1992–18. Province of British Columbia, Ministry of Energy, Mines and Petroleum Resources.

Biogeoclimatic zones of British Columbia from Ministry of Forests, Research Branch.

Note: This is not a karst map, but indicates only the known extent of most carbonate units in British Columbia.

FIGURE 3 *Limestone and dolomite occurrences in British Columbia with selected biogeoclimatic zones.*

The current status of karst inventories is a critical starting point for the development of the KISP. This is outlined in the following sub-sections:

- 2.1 describes current methodologies used by forest districts and regions in British Columbia,
- 2.2 reviews examples of "typical" karst inventory reports completed in British Columbia, and other karst inventories completed worldwide, and
- 2.3 summarizes the level of karst inventory–related information currently available in the publications of British Columbia government agencies.

2.1 Current Methodologies Used for Karst Inventories in British Columbia

2.1.1 General approach

Recreation resource inventories are required for planning purposes as part of the Forest Practices Code, and are usually carried out by the forest districts and licensees. A recreation resource inventory involves identifying, classifying, and recording the types and locations of recreation features, visually sensitive sites, recreational opportunities, rivers, trails, and interpretive forest sites. The recreation inventory is normally carried out at the 1:50 000 scale (or 1:20 000 on Vancouver Island and in the Lower Mainland). For most areas, karst and cave areas have been mapped as L5 polygons. More specific karst-related recreation feature codes were devised in 1996, as follows:

K00	Cave/karst features
K01	Cave
K02	Sinkhole
K03	Limestone plateau

The methods by which L5 polygon boundaries have been determined vary throughout the province. In some forest districts, after confirmation of the karst unit boundaries and adjustment of the L5 polygons, ground search methods are used to locate karst features and cave entrances. These methods include low-intensity reconnaissance walkabouts, moderately intensive grid pattern or judgemental searches, and high-intensity total search grids (see Section 5.0 for details). The ground search is usually concurrent with, or followed by, subsurface inspection of caves. This subsurface inspection can, depending on the cave resources encountered, lead to a complete multi-disciplinary subsurface inventory.

The Port McNeill and Campbell River Forest Districts have been at the forefront of karst inventory work in British Columbia, both in terms of field methodologies and in the number of karst inventories completed. Other forest districts and regions have been involved in karst inventories to a lesser extent. The sections below focus on the current karst inventory systems used by the Port McNeill and Campbell River Forest Districts.

2.1.2 Port McNeill Forest District

Reconnaissance (1:250 000 scale) cave/karst potential maps, completed in 1994, identify the main regions of karst in the Port McNeill District, and are used for strategic planning purposes (e.g., calculation of AAC net down).

L5 recreation polygons have been delineated for the entire district at a scale of 1:20 000. These are intended to include all potential surface karst areas, but, in some places, include non-karst recreational values. However, the intention for the future is that L5 (now called "K00") polygon boundaries should follow surface karst boundaries only. To obtain preliminary boundaries for L5 polygons, the boundaries of limestone-bearing units are taken from available bedrock maps (typically no finer than 1:50 000 scale) and superimposed on the boundaries of 1:50 000 scale terrain map polygons where karst has been identified (e.g., as -K on the terrain unit symbol). The resultant L5 polygon then becomes the outline of the two boundary types. Refinements to the boundaries of L5 polygons are made over time as karst inventories are carried out for particular areas and as the boundaries are checked in the field.

Approximately 20–30 karst inventories are estimated to have been carried out in the district for a range of scales—1:20 000, 1:10 000, and 1:5000. Most have focused on the location of significant karst surface features and cave entrances, and were combined with subsurface cave inspections and classification. Judgemental traverses appear to be used for ground search methods more often than grids.

2.1.3 Campbell River Forest District

The Campbell River District uses reconnaissance (1:250 000 scale) cave/karst potential maps in a similar fashion to the Port McNeill District. However, the various high, moderate, and low ratings of karst potential on the maps are occasionally used to provide some indication of areas where more detailed inventories should be focused.

Landscape-level inventories are currently done at 1:50 000 and 1:20 000 scales, and are used to refine the boundaries of karst units. This is usually done at the 5- or 20-year forest development plan stage. The boundaries are checked by field reconnaissance along creeks and roads. Once the surface extent of the karst units are known, they are mapped as L5 polygon boundaries.

Identification and mapping of karst features at the operational level is accomplished mainly by traversing the L5 polygons with grid ground searches. This is done at scales of 1:20 000 or 1:10 000. Typically, the grids are laid out by three workers, one surveying a centre line and two others (rovers) on either side zig-zagging back and forth. Karst surface features and cave entrances are identified and tied into the survey line, and subsurface inspections are carried out for cave classification. It is estimated that 30–50 of these types of karst inventories have been completed for the district.

Cave/karst impact assessment reports are required for any proposed forestry activity to assist with management decisions on karst areas. These reports may include statements on slope, terrain stability, soils, windfirmness, hydrology, vegetation, wildlife and fisheries, palaeontological values, and socio-economic concerns.

In some cases, the landscape- and operational-level inventories and the cave/karst impact assessments are combined into one detailed inventory.

2.1.4 Other districts and regions

Various data have been obtained from some of the other forest regions and districts in British Columbia. The North Coast Forest District uses the 1:250 000 karst potential maps for the Prince Rupert Forest Region to determine the location of karst areas and incorporate them into L5 recreation inventory polygons. The "Koo" system now used for recreation karst inventories is not in place in the North Coast District at the present time. Operational-type karst inventory reports have not been used in the relatively few karst areas that have been identified.

The South Island Forest District has used a combination of 1:50 000 bedrock geology maps and public (e.g., caver) input to identify L5 polygons. Only a few (approximately six) operational-type karst inventory reports have been completed for the district.

The Nelson Forest Region identifies karst as part of their recreation inventory mapping, and uses the current "Koo" system at a scale of 1:50 000. The recreation inventory is determined from a combination of forest cover maps, airphotos, and local karst/cave knowledge. Operational-type karst inventories have not been completed in any karst areas in the region to date.

In the Prince George Forest Region, karst information for L5 polygons has been derived mainly from bedrock geology maps and local knowledge. Only one reconnaissance/planning-type karst inventory report is known to have been completed in the region—for the Herrick Creek Watershed.

2.2 Review of Karst Inventory Reports

Reports reviewed for this section include the typical karst inventory reports completed for the B.C. Ministry of Forests and the forest industry, and examples of karst inventory reports from the rest of Canada and worldwide. The reports were examined for the following criteria:

- inventory objectives and end users,
- inventory scale,
- office review methods/materials (British Columbia reports only),
- field inventory methodologies used, and
- reporting standards/presentation (British Columbia reports only).

The review was not intended to criticize or evaluate particular methodologies or reporting styles, but rather to assess current activities. It is not anticipated that future karst inventory reports for British Columbia should be completed in a standard format, but rather that they should all include critical factors required to assess a particular karst area in a scientifically sound manner. Tables were developed to review the karst inventory reports for the criteria listed above (Tables 2 and 3). Some assumptions were made during the review process, particularly in terms of understanding objectives (not always clearly stated), the source of materials used (not always referenced), and the conclusions and recommendations made.

A general letter was sent to all regional and district offices of the B.C. Ministry of Forests, and interested parties overseas, introducing the KISP project and requesting inventory reports for review. A homepage with an annotated questionnaire survey was developed to assist correspondence with interested parties (**http://www.island.net/~subterra**).

Almost all of the British Columbia karst inventory reports reviewed were from the Port McNeill and Campbell River Forest Districts of

TABLE 2 *Review of typical karst inventory reports for the Ministry of Forests and forest industry in British Columbia*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-AI9240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
REPORT TYPES OR CATEGORIES																
Cave investigations (management)		X	X			X		X	X	X	X	X	X	X	X	X
Surface karst (cave entrance) management	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
Impact assessment														Z		
Karst aquifer/hydrological evaluation																
Karst ecology/biota evaluation																
Recharge/catchment area delineation								X								
Karst vulnerability/sensitivity assessment			X					X			X					
DATE OF PROJECT																
1982–1987																
1988–1992		X												X		
1993–1998	X		X	X	X	X	X	X	X	X	X	X	X		X	X
ESTIMATED PROJECT COVERAGE																
Regional (>1:200 000)																
Intermediate (>1:75 000 to <1:200 000)																
Planning (>1:15 000 to <1:75 000)											X	X				X
Detailed (>1:2500 to <1:15 000)	X	X	X	X	X	X	X	X	X	X			X		X	
Very detailed (< 1:2500)														X		
REPORT SETUP/DESCRIPTORS																
Cover/title page	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Date	Z	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Location	Z	Z	X	X	X	X	Z	X	X	X	X	X	X	X	X	X

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Prepared for	Z	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Prepared by	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Abstract or summary	X	X	X				X	X	X	X	X		X			
Acknowledgements		X	X				X	X	X	X	X					X
Table of contents	X	X	X				X	X	X	X	X		X	X		X
Section headings	X	X	X	X	X	X	X	X	X	X	X		X	X		X
Page numbers	X	X	X			X	X	X	X	X	X	X	X	X	X	X
OBJECTIVES OF INVENTORY																
To manage forest resources	X		X			X		X	X	X	X	X				X
To increase awareness of karst resources	X	X	X			X	X	X	X	X	X	X	X	X		X
To inform land use decisions													X			
To investigate karst groundwater systems																
To assess sensitive recharge zones			Z					X					Z			
To protect domestic water supplies																
To protect downstream resources/fisheries													Z			
To assess/manage/protect caves		Z				Z	Z	Z	X	X	X	Z	Z	X	X	X
INTRODUCTION AND BACKGROUND																
Site location	X	X	X			X	X	X	X	X	X		X	X	X	X
Terms of reference/scope of work			Z			Z	X	X	X	X	X		X	X		X
Local knowledge		X	X				X	X	X	X	X		X	X		X
Pre-cutblock/road layout	X	X	X				X			X	X					
Post-cutblock/road layout				X	X	X		X	X							

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Proposed harvesting methods																
Previous karst inventory work/reports		X	X					X	X	X	X		X	X		X
Regional geomorphology/geology	X	Z	Z			Z	X	Z	X	X	Z		Z	X		X
Biophysical setting	X		X			Z		X	X		X	Z		X		
Hydrological setting	X					X		Z			Z		X	X		
OFFICE REVIEW MATERIALS																
Topographical maps/data	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
Bedrock geology maps	X	X	X			X	X	X	X	X	X		X	X		X
Air photos	X	X					X	X	X	X	X		X	X		
Surficial geology/terrain maps		X	X					X								
Standards and protocols	Z	X	Z			X	X	X	X	X	X		X			
Hydrological/rainfall data																
Forest cover maps												X				
Terrestrial ecosystem/vegetation/soil maps																
Archeological surveys																
Fish/wildlife habitat maps																
Digital satellite imagery																
Photographs/videography																
Other reports (terrain stability, windthrow)																
Books and periodicals																
Unpublished records (e.g., cave surveys)																

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
FIELD INVENTORY METHODOLOGIES																
Field personnel names	X	X	X			X	X			X					X	X
Date/time/length of field work	Z	X	X			X	X		X	X						
Weather conditions during field work						X										
Aerial searching											Z					
Ground searching - walkabout															X	
Ground searching - judgemental traverse			X					X	X	X	X	Z	X			
Ground searching - single transect												X				
Ground searching - multiple traverses/grids	X	X		X	X	X	X									
Subsurface inspection - exploration																
Subsurface inspection - MOF classification	X	X	X				X	X	X	X	X	X				
Subsurface inspection - cave survey/map			X			X		X	X	X						
Subsurface - specific resource investigation																
Description of field markings/flagging	X			X	X					X	X	X				
Field instrument description (e.g., compass)		X	X							X						
Water tracing with dyes																
Water tracing with dyes and collectors																
Water flow measurements																
Water sampling for chemistry																
Water sampling for ph, Eh, etc.																
GPS use																

TABLE 2 *(Continued)*

		Cross River	Artlish River	Ransom Lake	022-Artlish	07-Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
RESULTS																	
Data presentation -	Tabular		X	X			X	X	X	X	X	X		X			
	Forms (e.g., FS 311)	X	X	X				X	X	X	X	X					
	Narrative	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Map presentation of karst features -	Polygons	X		X					X			X		X	X		
	Lines			X					X			X		X	X		
	Points	X	X	X	X	X		X	X	X	X	X	X	X	X	X	
	Symbol convention		X	X				X	X	X	X	X		X			
PRESENTATION OF DATA																	
TABLES			X	X			X	X	X	X	X	X		X			
Descriptive headings			X	X			X	X	X	X	X	X		X			
Numbered sequentially			X	X			X	X	X	X	X	X		X			
MAPS/FIGURES		X	X	X			X	X	X	X	X	X	X	X	X	X	
Digitally drafted			X	X				X	X	X	X	X		X	X		
Manually drafted		X			X	X	X						X			X	
Title/heading		X	X	X			X	X	X	X	X	X		X	X	X	
Scale		X	X	X	X	X	X	X	X	X	X	X		X	X	X	
North arrow		X	X	X			X	X	X	X	X	X		X	X	X	
Legend		X	X	X			X	X	X	X	X	X		X	X		
Traverse/grid locations					X	X						X					
DATA ANALYSIS METHODOLOGIES																	
Cave/karst management zones		Z												X	X		

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Qualitative cave/karst potential																
Hydrological analysis																
Recharge area delineation			Z					Z					Z			
Karst vulnerability assessment			X					X			X					
GIS mapping techniques																
DISCUSSION AND/OR INTERPRETATION	X	X	X			X	X	X	X	X	X	X	X	X		
CONCLUSIONS	X	X	X	Z	Z	X		X	X	X	X	X	X	X		X
RECOMMENDATIONS	X	X	X	Z	Z	X		X	X	X	X	Z	X	X	X	X
ADDITIONAL DATA/INFORMATION																
REFERENCES	X	X	X				X		X	X	X		X	X		X
BIBLIOGRAPHY	X															
GLOSSARY	X	X	X			X	X		X	X	X		X	X		X
APPENDICES	X	X	X			X	X		X	X	X		X	X		
PHOTOGRAPHS		X	X			X	X		X		X	X				
Numbered		X	X				X				X					
Annotation/descriptions		X	X			X	X				X	X				
VIDEOGRAPHY																
Verbal narrative																
LIMITATIONS																
Confidentiality statements		X	X				X				X					
Accuracy and reliability statements																
Statement on any missing information																

TABLE 2 *(Concluded)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Limiting field conditions (weather, windthrow)						X										
END USERS																
B.C. Ministry of Forests	X	X	X				X			X	X	X	X	X	X	X
Other government forestry agencies																
Municipal/regional land-use planners																
Government environmental agencies																
Forest industry				X	X	X		X	X							
Public																
Cavers																
Research agencies																

A Cross River cave/karst inventory. Prepared for Ministry of Forests by Island Karst Research. Spring 1993. Unpublished report. 22 p.
B Artlish River caves/karst inventory: Report on the ground search of Karst Feature Areas 2,3,4 and 5 Conducted for B.C. Ministry of Forests. September 1990.
C Cave/karst inventory in and about Ransom Lake, F.L. A19231. Conducted for Pacific West Coast Contract Logging. June 1996.
D Cave/karst features inventory report for Block 022, Artlish, F.L. A19231. Prepared for Pacific Forest Products Ltd. June 1993.
E Cave/karst features inventory report for Block 07, Artlish, F.L. A19231. Prepared for Pacific Forest Products Ltd. July 1994.
F Cave inventory of Block NE-60 and Block AR-165. Prepared for Canadian Forest Products. January 1994.
G Cave/karst features inventory report for F.L. A19240. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. Report date: March 1993.
H Cave/Karst inventory in and about Block DL-10. Conducted for Canadian Forest Products Limited, Englewood Logging Division. Report date: September 1994.
I Cave/karst inventory in Area 149, F.L. A19240. Conducted for Western Forest Products Ltd. September 1995.
J Cave/karst ground search for F.L. A19240. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. March 1994.
K Klaskish and East Creek karst survey. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. July 1996.
L Cave/karst features inventory, Nawitti Lake and Kains Lake Forest Area. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. March 1993.
M Karst mapping for the Glory 'Ole Area Management Plan. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. September 1994.
N Resource inventory and management plan for the Upana Caves, T.F.L 19, Kyuquot Provincial Forest. Prepared by the Campbell River Forest District. March 1988.
O Report on caves in the Chapple Inlet area of Princess Royal Island by Christopher Gordon. February 1996.
P Cave/karst inventory of the Duncan Forest District, B.C. Ministry of Forests. March 1993.

NOTE:
X Clearly apparent
Z Partially apparent (some judgement involved)

TABLE 3 *Review of other karst inventory reports in Canada and worldwide*

	Tuxekan	Lab Bay	Grand Rapids	New Melons	Cullagh	Interlake	White Ridge	Cougar	Nahanni	Great Bear	Snaring	Jags	Maligne	Quatsino	Regions	Grottes	Coronation
	CC	DD	EE	FF	GG	HH	I I	JJ	KK	LL	MM	NN	OO	PP	QQ	RR	TT
REPORT TYPES OR CATEGORIES																	
Cave investigatons (management)			X	X		X			X		X			X		X	
Surface karst mangement	X	X	X			X		X	X	X	X	X			X	Z	
Impact assessment				X				X		X							
Karst aquifer/hydological evaluation							X			X			X	X			
Karst ecology/biota evaluation						X		X				X					X
Water tracing for recharge area delineation	X	X			X												
Karst vulnerability/sensitivity analysis	X	X															
DATE OF PROJECT																	
Pre-1987				X			X	X	X	X	X		X	X	X		
1987–1992			X			X						X					
1993–1998	X	X			X											X	X
RANGE OF PROJECT SCALE																	
Regional (>1:200 000)														Z	X		
Intermediate (>1:75 000 to <1:200 000)		X								X		Z	Z		X		Z
Planning (>1:15 000 to <1:75 000)		X	Z	Z	X		X		X	X	Z						
Detailed (>1:2500 to <1:15 000)					X	X		X									
Very detailed (< 1:2500)			X	X		X		X	X		X	X	X	X		X	Z
STATED OBJECTIVES																	
To manage forest resources	X	X															
To increase awareness of karst resources	X	X	X			X	X	X	X		X	X	X	X	X	X	X
To inform land-use decisions				X	X			X		X		X					
To investigate karst groundwater systems										X			X	X			

TABLE 3 *(Continued)*

	Tuxekan	Lab Bay	Grand Rapids	New Melons	Cullagh	Interlake	White Ridge	Cougar	Nahanni	Great Bear	Snaring	Jags	Maligne	Quatsino	Regions	Grottes	Coronation
	CC	DD	EE	FF	GG	HH	I I	JJ	KK	LL	MM	NN	OO	PP	QQ	RR	TT
To assess sensitive recharge zones	Z	Z			X												
To protect domestic water supplies																	
To protect downstream resources/fisheries	Z	Z															
To assess/manage/preserve caves																	
FIELD INVENTORY METHODOLOGIES																	
Aerial searching									X		X	X					
Ground searching - walkabout						X					X	X			X	X	
Ground searching - judgemental traverse	X	X					X	X	X	X				X			X
Ground searching - single transect																	
Ground searching - multiple traverses/grids																	
Subsurface inspection - exploration																	
Subsurface inspection - MOF classification																	
Subsurface inspection - cave survey/map				X		X	X	X	X		X			X	X	X	
Subsurface - specific resource investigation				X		X											
Field instrument description (e.g., compass)																	
Water tracing with dyes					X												
Water tracing with dyes and collectors	X	X					X						X				
Water flow measurements					Z		X			X			X				
Water sampling for chemistry							X			X			X	X			
Water sampling for ph, Eh, T, etc.							X			X				X			
GPS equipment																	
DATA ANALYSIS METHODOLOGIES																	
Cave/karst mangement zones																	
Qualitative cave/karst potential																	

TABLE 3 *(Concluded)*

	Tuxekan	Lab Bay	Grand Rapids	New Melons	Cullagh	Interlake	White Ridge	Cougar	Nahanni	Great Bear	Snaring	Jags	Maligne	Quatsino	Regions	Grottes	Coronation
	CC	DD	EE	FF	GG	HH	II	JJ	KK	LL	MM	NN	OO	PP	QQ	RR	TT
Hydrological system analysis							X			X			X	X			
Recharge area delineation	X	X			Z												
Karst vulnerability assessment	X	X															
GIS mapping techniques	X	X			X												
PRINCIPAL END USERS																	
B.C. Ministry of Forests																	
Other government forestry agencies	X	X															X
Municipal/regional land-use planners																	
Government environmental agencies				X	X			X	X		X	X			X	X	
Public and cavers					X	X										X	
Research agencies							X						X	X			X

CC Karst vulnerability assessment report, Tuxekan Island, Alaska. 1994. Completed for the USDA, Forest Service.
DD Final karst vunerability assessment report, Phase II – Site specific verification study, Lab Bay environmental impact statement, Prince of Wales Island, Alaska. 1995. USDA, Forest Service.
EE Karst investigations in Palaeozic carbonates of the Grand Rapids Uplands and Southern Interface. Manitoba Energy and Mines. Report of Field Activities. 1988. pp. 143–156.
FF An inventory and evaluation of the cave resources to be impacted by the New Melons resevoir project, Calaveras and Tuolumne Counties, California. Submitted to the Sacramento District Office of the U.S. Army Corps of Engineers, 1978.
GG Environmental change and land management in the Cuilagh karst, Northern Ireland by John Gunn, pages 195-207. In "Geomorphology and Land Mangement in a Changing Environment." Edited by D. McGregor and D. Thompson. 1995.
HH Caves in Manitoba's Interlake Region. From surveys conducted by the Speleogical Society of Mantioba. 1991.
II The Hydrology of an alpine karst, White Ridge, Vancouver Island. Unpublished MSc Thesis. K. Ecock. McMaster University. 1994.
JJ Cougar Valley – Nakimu Caves, Glacier National Park, British Columbia. Volumes I and II. Resource inventory and environmental impact assessment. Prepared for Parks Canada by Hardy Associates Ltd. 1978.
KK Final report upon cavern and allied researches in the First Canyon Park, S. Nahanni River, N.W.T. Completed for National Historic Parks Branch by Cave and Karst Research Group of Canada. 1971.
LL Morphology, hydrology and hydrochemistry of karst in permafrost terrain near Great Bear Lake, Northwest Territories. National Hydrology Research Institute Paper No. 11. by R.O. van Everdingen. 1981.
MM Snaring karst exploration, Jasper National Park. Joiint project by Parks Canada and Alberta Speleological Society. 1984.
NN Alsaka research areas, 2: Limestone Jags. Gen. Tech rep. PNW-GTR-237. USDA, Forest Service, Pacific Northwest Research Station. 58 p.
OO Karst geomorphology and hydrology of the Lower Maligne Basin, Jasper, Alberta. Unpublished MSc thesis by M.C. Brown, McMaster University. 1970.
PP Karst development and groundwater flow in the Quatsino Formation, Northern Vancouver Island. Unpublished MSc thesis. W.R.P. Miles. McMaster University. 1981.
QQ Theme and resource inventory study of the karst regions of Canada. Completed for National and Historic Parks Branch by D. Ford and J. Quinlan. 1973.
RR Les grottes du sud-est du Nouveau-Brunswick. Open file 94-6, Natural Energy and Resources, New Brunswick.
TT Inventory and assessment of ecological relationships between cavernicolus (cave-associated) invertebrate species and their interactions in representative karst ecosystems on carbonate terrain in the Ketchikan area Tongass National Forest. Part II Coronation Island. Completed by Karst Biosciences, Kent Carlson. 1996.

NOTE:
X Clearly apparent
Z Partially apparent (some judgement involved)

Northern Vancouver Island. One karst inventory report was obtained from the South Island Forest District. No karst inventory reports were obtained from known interior karst areas such as Prince George or Nelson. No particular methods were involved in selecting reports for review other than to obtain a cross-section of inventories completed by a variety of workers/contractors.

Other karst inventory reports reviewed included government publications, consultant reports, and research theses completed for a range of end users in Canada and worldwide. No particular method was used in the selection of the reports other than availability and, if possible, some association with forestry activities. Some of the reports focused solely on one aspect of karst (e.g., hydrology, biota, caves). Reports reviewed included the following:

- two karst vulnerability assessment reports from Southeast Alaska,
- three theses investigating karst hydrology in British Columbia,
- two karst biota inventories from Southeast Alaska,
- two karst resource inventories—Canada-wide and South Nahanni River, NWT,
- a geomorphology, natural resource, and impact assessment for Nakimu Caves, British Columbia,
- cave-oriented inventories, Manitoba (x2), New Brunswick, and Jasper National Park, and
- a cave resource impact assessment from California.

2.2.1 Review findings for typical British Columbia karst inventory reports

The main objectives of the British Columbia karst inventory reports reviewed (Reports A to O) were to assist in the forest management of surface karst features, cave entrances, and cave systems. Little or no consideration was given in the reports to karst hydrological systems, karst biota, or downstream resources and impacts. An attempt was made in three reports (C, H, and K) to assess karst vulnerability and recharge areas. Most of the reports were completed in the last 5 years. Most were completed at a detailed operational scale of 1:5000; however, two reports (K and L) were completed at the planning-level scale of 1:20 000. Two cave/karst management plans and one cave report were also included in this review (Reports M, N, and O, respectively).

Background information in the reports was confined to topographic and bedrock maps. It was assumed that airphotos were used in most cases; however, they were not always specifically referenced with a flight line, number, and year. Terrain maps and surficial geology maps were only sparingly used (Reports B and C). Other indirect background information (e.g., hydrological/rainfall data, fish habitat maps) was not addressed. The principal government standards and protocols used for the completion of the inventory reports included:

- The Cave/Karst Management Handbook for the Vancouver Forest Region, 1994, and
- A Method to Manage the Cave/Karst Resource Within British Columbia's Provincial Forest: Interim Guidelines for the Vancouver Forest Region, 1990.

Ground searching, by either judgemental traverses (based on a predetermined rationale of karst distribution) or multiple-transect grids, were the main field methodologies used (see Section 2.1). Most of the subsurface inspection work included a combination of classifying caves according to B.C. Ministry of Forests requirements (e.g., the F311 form) and maps covering the entrance and a portion of the initial cave area. No dye tracing was carried out to investigate hydrological flows. Background details of field work were generally incomplete, missing such items as weather conditions, number of days/hours in the field, and field instruments used.

The standard of reporting varied considerably, both in terms of report content and presentation. General locations of areas of interest were usually described adequately, but regional location maps were not present in all cases. In some cases, the objectives or scope of the work, detailing why the inventory was being carried out, were not present. Very few details were provided about the types of proposed forest activities, (e.g., harvesting methods and road construction techniques). Road locations appeared to be rarely assessed. In most cases, the regional geological and geomorphic setting was only partially described, with little description of limestone lithology or bedrock structures. Some bedding measurements were recorded in some reports, but no other structural bedrock data (e.g., joints/faults) were typically present.

Map presentation varied from hand-drafted maps with point locations for surface karst features to coloured digital maps with polygons depicting karst vulnerability ratings. Some maps had no legends, titles, or north arrows. The traverse or grid locations for areas covered by the inventories were commonly not present on maps, and were found only in Reports D, E, and K. This is important for assessing the coverage of a particular karst unit/cutblock/road, in order to quickly evaluate which areas have been examined and which have not.

In general, very little analysis of the karst data was done; for example, correlating subsurface features with surface features, developing management zones, providing karst vulnerability assessments, or delineating recharge areas. Exceptions to this were Reports C, H, and K, where vulnerability mapping and some recharge area delineation were carried out, and Report M, where management zones were delineated. Most reports provided recommendations for forestry activities that primarily focused on prescriptions for surface karst features, cave entrances, and cave systems.

Almost no reports provided information on any limitations of the work. For example, few detailed the areas not covered by the inventory, the reliability of the field work completed, or any limiting factors such as bad weather. Data confidentiality statements were provided in Reports B, C, G, and K.

It is apparent that the focus of most of the inventory reports was to locate and manage for specific surface karst features, cave entrances, and cave systems. Very little focus was placed on the karst system as a whole, and there was minimal recognition of karst hydrology or biota as part of a standard inventory process.

No attempts were made to analyze any of the inventory data, such as developing a suitable or simple geological/geomorphological/hydrological

model for the karst system. No dye tracing was carried out, nor were any attempts made to try and understand the subsurface hydrological system. No use was made of cross-sections to interpret or understand the subsurface extent and three-dimensional nature of the karst units.

2.2.2 Review findings for other karst inventory reports in Canada and worldwide

The general objectives of these other karst inventory reports varied significantly. Some focused on specific aspects of karst (e.g., biota, hydrology, caves), while others were very broad in scope, covering a range of karst parameters. The scales also varied from regional or countrywide (e.g., Report II) to very site- and cave-specific (e.g., Report RR). The underlying objective of most reports was to increase the general awareness of karst resources. However, each report had project-specific objectives. For example, the inventories from southeast Alaska (Reports CC and DD) focused on forest management, Reports FF and GG were to help with land management decisions for the protection of cave resources, and Reports EE and RR were concerned with cave exploration within karst areas.

In terms of ground-searching methodologies, most surface karst areas were examined by a combination of walkabout and judgemental traverses; no transects or grid systems were used. Aerial searching was conducted in some of the more regional and inaccessible areas, and was used for identifying likely sites for ground searches. Cave surveying and mapping were the principal subsurface inspection methods, and were used for some of the regional inventories (e.g., Report KK). Water tracing with dyes was used in the hydrology-specific inventories (e.g., Reports II and PP), in the southeast Alaska vulnerability assessment reports (Reports CC and DD), and in a cave impact assessment report (Report GG). Water chemistry and flow measurements were taken only for the hydrology-specific reports (Reports II, LL, and OO). The end users of these reports were principally government forestry or environmental agencies, and research institutes.

Karst vulnerability analysis, recharge delineation, and GIS mapping methods were used only in the more recent reports (CC, DD, and GG). Detailed hydrological analysis was carried out only for the hydrology-specific reports.

2.3 Karst-related Information in Government Publications of British Columbia

The first objective of this sub-section is to assess and synthesize the level of karst inventory–related information currently available in the publications of British Columbia government agencies. The second is to determine what inventory methodologies could be either incorporated into the KISP or, alternatively, improved to increase the awareness of karst systems. A variety of British Columbia government publications was examined, including publications of the Resource Inventory Committee (RIC), publications of BC Environment, Forest Practices Code (FPC) Guidebooks, and British Columbia Geological Survey documents. The Cave/Karst Management Handbook for the Vancouver Forest Region, 1994, and the FPC Cave Management Guidebook (draft) also provide guidance for karst inventories (see Section 2.1), but focus mainly on cave classification and management, an area outside the scope of this project.

2.3.1 Resource Inventory Committee (RIC)

A manual and digital search (by ForestViews software) was carried out on the RIC to identify any information related specifically to karst, limestone, carbonate, or caves. Publications considered to have relevance to karst inventories were:

- Guidelines and Standards to Terrain Mapping in British Columbia,
- Standards for Terrestrial Ecosystems Mapping in British Columbia,
- Specifications and Guidelines for Bedrock Mapping in British Columbia,
- Terrain Stability Mapping in British Columbia: A Review and Suggested Methods for Landslide Hazard and Risk Mapping,
- Terrain Database Manual: Standards for Digital Terrain Data Capture in British Columbia (interim), and
- Groundwater Mapping and Assessment in British Columbia, Vols. I and II.

Guidelines and Standards to Terrain Mapping in British Columbia (GSTM-BC) The principal objective of the GSTM-British Columbia is "to define common standards and methods for the collection and presentation of terrain data." The guidelines show how this information can be used to develop secondary derivative maps (e.g., geological hazard, slope stability) for resource and land management purposes. The publication is closely linked to the Terrain Classification System of British Columbia (TCS-BC) and the Terrain Database Manual for British Columbia (TDM-BC). Karstification processes and karst features are briefly mentioned throughout. The specific terms: karst, karst depression, karst processes, limestone pavement, and sinkholes, are defined in the glossary. Features specific to karst are included in the symbols appendix at the end of the publication, and include those for cave, large sinkhole/karst depression, and small sinkhole/karst depression. Cartographic definitions and details for defining each of the features are provided.

A series of hydrological and hydrogeological features is also outlined. These include: groundwater divide, surface water divide, groundwater flow (various scales and levels of certainty), springs (various types), disappearance of surface drainage, reappearance of surface drainage, surface water drainages (dry, intermittent, perennial), surface water gullies (dry, intermittent, perennial), and swamps (big and small). These hydrological features do not appear karst-specific, but they could have some potential use for the mapping of karst hydrological systems/catchment areas.[4] Most of the methodologies for project organization, field work, and map compilation could be used to assist in the development of karst mapping/inventory procedures, particularly at the planning scales of 1:50 000 and 1:20 000. Details on how terrain mapping methods could be used at the planning level of karst inventory are provided in Section 4.0.

Standards for Terrestrial Ecosystems Mapping in British Columbia (STEM-BC) The STEM-BC is similar to the GSTM-BC in that karst is mentioned only in passing. It is primarily noted under the bioterrain mapping methods in Appendix B, where limestone or carbonate is

[4] Karst catchment – the subaerial surfaces upon which water contributes to the recharge of a karst aquifer (not to be confused with topographic watersheds and drainage basins).

identified as a bedrock unit that can contain "caves, karst, large cracks and joints, fault lines" as well as "unique flora, fauna and habitat." Bioterrain mapping methodologies rely heavily upon surficial characteristics and processes taken from the Terrain Classification System of British Columbia (TCS-BC). A useful table for the classification of sedimentary rocks is included in Appendix K. Two mentions of carbonate seepages are identified in Appendix J under the site series modifiers for IDFdm206BH- Scrub birch-Horsetail and IDFdm207SHSxw-Horsetail.

Specifications and Guidelines for Bedrock Mapping in British Columbia (SGBM-BC) The SGBM-BC publication describes a methodology for data collection and presentation, and for the production of geological bedrock maps. Karst is not specifically mentioned; however, it does recommend the use of standard geological texts for the classification of carbonates (e.g., Dunham 1962; Folk 1962). Many of the project planning procedures, field survey methods, data synthesis ideas, and map production techniques could be used for karst inventory mapping methods at the reconnaissance and planning levels (see Sections 3.0 and 4.0, respectively).

Terrain Stability Mapping in British Columbia: A Review and Suggested Methods for Landslide Hazard and Risk Mapping (TSM-BC) The TSM-BC publication is closely linked to the GSTM-BC and TCS-BC publications. No specific reference to karst is made within the TSM-BC; however, some of the mapping concepts and methodologies may have applications in developing the KISP. Of particular interest is Section 2.2, in which the various definitions of hazard, consequence, and risk are outlined. These are defined with reference to landslides, but could also be considered with respect to karst vulnerability (see Section 6.0).

Terrain Database Manual: Standards for Digital Terrain Data Capture in British Columbia (TDM-BC) This manual was compiled in conjunction with the GSTM-BC, STEM-BC, and TSM-BC. Its purpose is to establish "procedures and rules for the digital capture, storage and delivery of terrain data for GIS and data base systems so that they are suitable for digital data exchange between business, industry, the public and government." The manual covers the entry of terrain information on a terrain data form, digital data specifications for terrain mapping in GIS, and terrain data entity relationship diagrams.

Groundwater Mapping and Assessment in British Columbia, Vols. I and II (GMA-BC) These documents describe a dual-level groundwater mapping and assessment process that considers climatic, hydrologic, geologic, topographic, ecologic, and soil factors in hydrogeological settings. The Level 1 assessment gives an approximation of the groundwater regime and a qualitative overview of groundwater conditions. The parameter measurements are derived from available information, without detailed reconnaissance. The system relies on the DRASTIC model; an overlay and index method combining maps of parameters considered influential in contaminant transport. The DRASTIC acronym stands for the following parameters: D - depth to water; R - net recharge; A - aquifer media; S - soil media; T - topography or slope; I - impact of vadose zone media; and C - hydraulic conductivity of the aquifer.

The Level 2 assessment is a multi-phased study, beginning with the acquisition of existing information. The information search and analysis tasks are followed by a field reconnaissance survey of controlling factors. Water wells and springs are inventoried to determine yield characteristics and hydrochemistry. Recommendations for further study and assessment are also prepared. The DRASTIC model could potentially be used to assess the vulnerability of karst groundwater during forest management activities. Most of the parametric values for a Level 1 assessment are readily determined from existing sources of information, such as geological maps, topographical maps, terrain maps, air photos, geological reports, climatological records, spring records, and published speleological investigations. However, some workers in karst hydrology (e.g, Aley and Aley 1993) have found that while DRASTIC demonstrates that karst areas are at risk to groundwater contamination, it is not detailed enough for making integrated land-use decisions.

2.3.2 BC Environment publications

The Terrain Classification System for British Columbia: Version 2.0 (TCS-BC) outlines a scheme for "the classification of surficial materials, landforms and geological processes," and is a fundamental part of the GSTM-BC and STEM-BC. Version 2.0 was completed in 1997, and is an updated and expanded edition of a 1988 publication. It is specifically designed to provide an inventory of terrain features in a landscape to show their spatial distribution, extent, and location. The fundamental feature of the system is the "terrain unit symbol," which is comprised of a group of letters, so arranged that they provide information on the characteristics of a particular terrain polygon. This information can include descriptions of surficial material type and texture, surface expression, geological processes, and qualifying descriptors.

The symbol "-K" is used as a specific process modifier at the end of the terrain unit symbol to identify karstification on soluble bedrock, and is intended to include a broad variety of karst features (e.g., uvalvas, caves, surface etching, and limestone pavements). Of particular interest to the KISP are the "geomorphological process subclass codes" that are attached at the end of the process modifiers for mass movement (-R), avalanches (-A), fluvial (-F), and permafrost (-X). These subclass codes provide "space" in the terrain unit symbol for additional qualifiers regarding geomorphic processes, and could be possibly adapted, in a rudimentary fashion, to indicate the intensity of karst development. Bedrock classification codes have also been added to the updated version and provide detailed descriptors for various types of carbonate bedrock. The codes are intended to be added to the end of the "R" symbol that is used to indicate the presence of bedrock. Phase 2 of the planning-level karst inventory describes modifications to the TCS-BC that could be used to include further karst information (see Section 4.3).

2.3.3 Forest Practices Code (FPC) guidebooks

FPC Guidebooks are limited in their mention of karst inventory–related information. Most of the related material is in the Cave Management Guidebook (draft). However, specific aspects (indicated in italics) of other FPC Guidebooks could have some uses for karst inventory methodologies:

- Riparian Management Area Guidebook (December 1995) - *Stream, wetlands and lake classification. Channel width measurements.*
- Community Watershed Guidebook (October *1995) - Water quality monitoring.*
- Gully Assessment Procedure Guidebook (December 1995) - *Methods for measuring gully sidewalls and channels. Holistic system approach to evaluating potential gully hazards and their impacts.*
- Coastal Watershed Assessment Procedure Guidebook (September 1996) - *Measurement of stream flow and catchment areas.*
- Interior Watershed Assessment Procedure Guidebook (September 1995) - *Measurement of stream flow and catchment areas.*
- Hazard Assessment Keys for Evaluating Site Sensitivity to Soil Degrading Process Guidebook (June 1995) - *Methods for measuring soil types, thickness, texture, drainage, slope gradients, and slope characteristics.*
- Mapping and Assessing Terrain Stability Guidebook (April 1995) - *Terrain survey intensity levels, map scales, classification and mapping conventions, and terrain reports.*
- Fish Stream Identification Guidebook (July 1995) - *Methods for identifying fish streams. Measurement of channels, gradients, and reaches; and need for fish surveys.*
- Channel Assessment Procedure Guidebook (December 1996) - *Identifying and classifying surface channel reaches.*
- Biodiversity Guidebook (1995) - *Managing calcareous bedrock exposures.*

It would be valuable to include more karst-related information in FPC guidebooks and other documents as they are revised over time.

2.3.4 British Columbia Geological Survey publications

Two useful "inventory-type" documents on karst bedrock materials have been completed by the British Columbia Geological Survey Branch:

- Limestone and Dolomite Resources in British Columbia by P. Fischl (Open File 1992-18), and
- Gypsum in British Columbia by S.B. Butrenchuk (Open File 1991-15).

Both publications document the occurrence of karst bedrock materials from a mineral exploration/mining perspective. Little or no mention of surface or subsurface karst features is made; however, the publications do document the extent, location, and type of bedrock materials present, and this would assist in determining the potential for karstification. References to more detailed maps and other site-specific publications/reports are also made. Overall, this information is considered essential for the reconnaissance-level karst inventory.

Another valuable source of information on karst bedrock materials can be found on the Ministry of Energy and Mines website under MINFILE, which contains maps and data on limestone, dolomite, and gypsum occurrences in British Columbia. It is also available in hard copy at Crown Publications, Victoria, B.C.

2.3.5 Other publications

Other government publications that could supply karst inventory–related information include:

- British Columbia archeological impact assessment guidelines. 1994. *(Specific mention of landforms, caves, and springs within inventory and assessment methodology.)*
- British Columbia archeological site inventory form guide. *(The site form and guide consider potential karst features such as rock shelters, caves, and springs.)*
- Green, R.N. and K. Klinka. A field guide for site identification and interpretation for the Vancouver Forest Region. 1994. *(Specific mention of limestone bedrock and calcareous soils.)*
- Pojar, J. and A. MacKinnon. Plants of Coastal British Columbia including Washington, Oregon and Alaska. 1994. *(Specific mention of carbonate bedrock exposures, calcareous soils, calciphilic plants, caves, and crevices.)*

3.0 PROPOSED RECONNAISSANCE- OR STRATEGIC-LEVEL KISP (1:250 000 MAP SCALE)

3.1 Objectives and Approach

The principal objective of the reconnaissance- or strategic-level karst inventory is to carry out a regional 1:250 000 scale evaluation for karst potential. This inventory level provides a coarse filter in which terrain underlain by karstified bedrock is flagged and identified. Bedrock geology maps can identify the principal bedrock types and units that are likely to develop karst (i.e., limestone and dolomite). However, they give no indication of the intensity of karst development or the importance of composite geological units in which the potential karst-forming bedrock may form a significant or small portion.

Suggestion 1. At a minimum, it should be possible to obtain regional bedrock maps covering a particular forest district or region and highlight the major carbonate formations. Without any further effort this will highlight the most likely karst-bearing formations.

It is not the intention of the reconnaissance karst inventory to delineate specific cave/karst sites or features, but rather to qualitatively rate terrain for potential karst development. These maps should not be used as direct overlays for planning- or operational-level inventories, because their regional scale (1:250 000) is unlikely to provide accurate polygon boundaries/lines at more detailed scales (e.g., 1:20 000 or 1:5000). Typically, the more detailed karst inventories will require field work and/or mapping to verify the distribution of the karst units and the degree of karstification.

A preferred approach for the reconnaissance-level inventory is to develop "karst potential" maps that can predict the likelihood and level of karst development within various geological units. The karst potential mapping can be used to evaluate two principal criteria:

- **Criterion 1** - the likelihood of karst-forming bedrock (e.g., limestone) to occur within a specific geological unit (or polygon), and
- **Criterion 2** - the intensity of karst development in a particular type of karst-forming bedrock.

Distinguishing between these two criteria could be useful during forest development planning. For example, a geological unit with a small well-karstifed limestone component may require different management/ planning strategies from a similarly rated geological unit that has a large, but poorly karstified, limestone component.

Suggestion 2. For reconnaissance-level inventories of karst potential, it is suggested that the two principal criteria are examined separately: Criterion 1, the likelihood of karst-forming bedrock to occur within a specific geological unit, and Criterion 2, the intensity of karst development in a particular type of karst-forming bedrock.

Additional confirmatory criteria, such as the presence of existing karst features, including both caves and surface karst features, can be used to add a level of confidence to the karst-potential rating of a particular unit. This evidence is highly dependent on the level of inspection/assessment for a particular unit or region.

Two previous reconnaissance cave/karst potential mapping projects have been carried out for the Vancouver and Prince Rupert Forest Regions using manual overlays and analysis (Stokes 1994; 1995a; 1995b). In both projects, 1:250 000 scale NTS topographic sheets were used as base maps, while bedrock geology maps of various scales (1:50 000 to 1:250 000) and ages were used to determine the presence of limestone-bearing units. The locations of these units were transferred as polygons onto the 1:250 000 base maps. The polygons were then split or grouped to assist in assigning cave/karst attribute data. These data included the character of the limestone unit, the number of known caves, the presence of major surface karst features, and the level of inspection. The information was tabulated for each map sheet, and a judgemental estimate from low to high cave/karst potential was provided for each of the polygons. These maps are currently used by some forest districts for strategic planning purposes, and, in some cases, for identifying priority sites for landscape- (planning-) level karst inventories. A trial reconnaissance cave/karst mapping project was carried out for northern Vancouver Island (Stokes et al. 1997) using digital (GIS) mapping techniques. This project showed how it was possible to combine and analyze digital bedrock polygons with cave/karst data, and produce maps for overall cave/karst potential and individual attributes (e.g., cave density).

3.2 Methodology

In order to develop a methodology for a regional-scale evaluation of karstification, the fundamental karst-forming process of water circulation and dissolution of bedrock must be closely considered. The greater the circulation, the greater the bedrock dissolution and the higher the intensity of karst development. Hydrogeologically, this process requires: i) water rich in carbon dioxide to recharge the system, ii) sufficient permeability to allow water flow to flush through the system, and iii) a discharge area to allow water to exit from the system.[5] The hydrogeologic setting of karst is difficult to determine directly; however, it is controlled by a variety of closely inter-related attributes, including:

- bedrock lithology (BL),
- tectonic/structural setting (tss),
- unit thickness (UT),
- topographic landform position (TP),
- vegetation cover (vc),
- soil cover (sc), and
- climatic setting (cs).

These attributes are relatively easy to determine at a regional scale from mapping, published, and local sources. However, they do not take into consideration the time factor, which might have played an important role in the karstification history of a particular unit. For example, the topographic landform setting provides an indication of present-day karst development in a particular unit, but earlier karstification of the unit might have occurred under a different topographic setting and hydrological regime. Climatic setting is similar to topographic position in that only the present-day climate can be easily assessed. For example, a unit in an area with high rainfall today might have had quite a different climate ten thousand, or even a thousand, years ago. Vegetation and soil cover attributes are closely related to climate and topographic position and hence, in some respect, are time dependent.

It is anticipated that the reconnaissance karst inventory will be an office-based study involving the collation and analysis of existing data. The suggested methodology includes the identification of karst-bearing units/polygons from existing 1:250 000 digital bedrock maps, and a rating analysis of the bedrock lithology combined with other available bedrock information (e.g., structural setting, unit thickness) and terrain and environmental attributes (e.g., climate, topographic position, vegetation/soil cover).

3.2.1 Preparation of digital base map and data

Regional 1:250 000 digital bedrock maps have been completed by the British Columbia Geological Survey Branch (BCGSB) for all of British Columbia. They are as follows:

- Vancouver Island - Open File 1994-6

[5] For simplicity, karst development in elevated or mountainous terrain was assumed as the likely dominant type of hydrological system in British Columbia. In this case, meteoric water and groundwater are the principal solutions present in the system. Other site-specific hydrological systems and waters can also develop karst, such as might be related to hydrothermal activity, acidification of waters related to sulphides, and fresh and salt water interactions during changes in land and sea levels.

- Cariboo/Chilcotin Area - Open File 1994-7
- Kootenay Area - Open File 1994-8
- Nass-Skeena - Open File 1994-14
- Mid-Coast - Open File 1994-17
- Northeast British Columbia - Open File 1995-6 and 1995-24
- Northwest British Columbia - Open File 1996-11

These maps were compiled as part of the BCGSB's Mineral Potential Project and depict the distribution of geological units and major structures. Information for the maps was obtained from previously published maps of the BCGSB and the Geological Survey of Canada, and from scientific journals, unpublished theses, mineral assessment reports, and property files. The open file reports can be obtained directly from Crown Publications, Victoria, B.C., or the maps can be viewed and downloaded from the Internet at the following web site: **http://www.em.gov.bc.ca/geology**. These digital bedrock data can be readily incorporated into GIS software such as ArcView. Various layers are present within the files, including coastline, lakes, islands, boundaries of geological units, structural features (e.g., faults), and labels for geological units. The base maps used for these compilations were taken from Digital Elevation Model (DEM) data reconstructed into a Terrain Resource Information Mapping (TRIM) format at a scale of 1:250 000. Additional information on topography, river systems, and roads can be obtained in digital format if required. Forest district and regional boundaries are provided on district recreation maps and 1:250 000 NTS maps.

3.2.2 Identification and rating of potential karst-bearing units

From the bedrock legends associated with the digital maps, all potential karst-bearing units should be identified and highlighted (see Figure 4). This should include both major limestone units and units within which limestone is a component. These units are usually classified according to a stratigraphic code system based on rock characteristics, fossil content, and geological age (see SGBM-BC, pp.29–34). In practice, the most likely units encountered at a regional mapping scale would be groups, formations, or complexes. The boundaries of these units can be highlighted, and the boundaries of other non-karst-bearing units digitally dissolved.

Geological input from bedrock geologists familiar with the region should be obtained to assist in the identification of potential karst-bearing units, particularly where limestone is a small component of a geological group or formation. Geologists from the Geological Survey of Canada, the British Columbia Geological Survey, the mining/exploration industry, or local consultants could provide useful information required for determining Criteria 1 and 2.

Criterion 1 Determination - Likelihood for karst-forming bedrock to occur In order to determine the likelihood of karst-forming bedrock (e.g., limestone) occurring within a specific geological unit (or polygon), it is necessary to estimate the proportion of limestone present. In practice this is difficult, as limestone within a unit can occur in a combination of ways, such as a series of thin layers or as isolated lenses. However, a geologist familiar with a particular unit should be able to provide a "best guess"

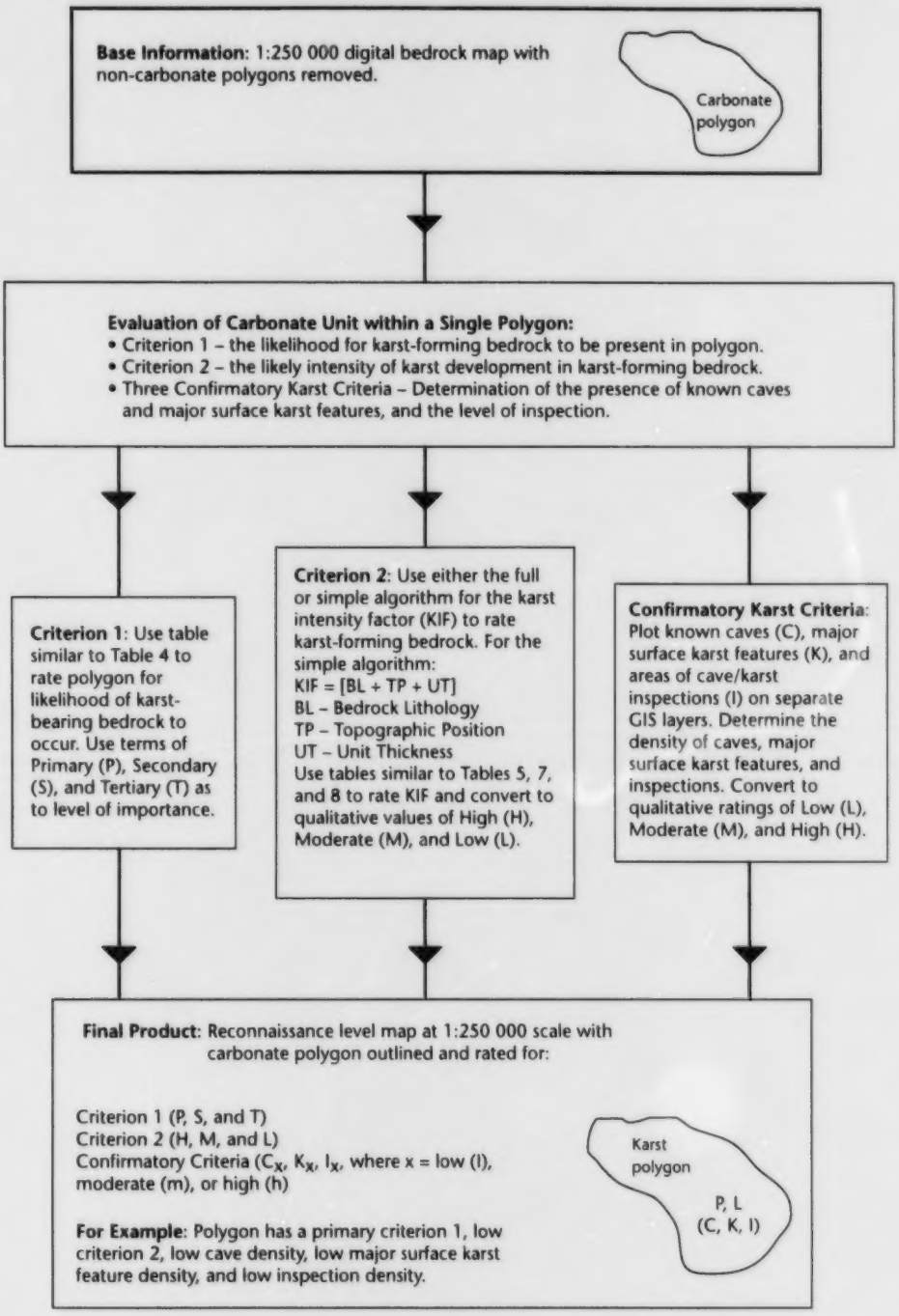

Base Information: 1:250 000 digital bedrock map with non-carbonate polygons removed.
Carbonate polygon
Evaluation of Carbonate Unit within a Single Polygon:
• Criterion 1 – the likelihood for karst-forming bedrock to be present in polygon.
• Criterion 2 – the likely intensity of karst development in karst-forming bedrock.
• Three Confirmatory Karst Criteria – Determination of the presence of known caves and major surface karst features, and the level of inspection.
Criterion 1: Use table similar to Table 4 to rate polygon for likelihood of karst-bearing bedrock to occur. Use terms of Primary (P), Secondary (S), and Tertiary (T) as to level of importance.
Criterion 2: Use either the full or simple algorithm for the karst intensity factor (KIF) to rate karst-forming bedrock. For the simple algorithm:
KIF = [BL + TP + UT]
BL – Bedrock Lithology
TP – Topographic Position
UT – Unit Thickness
Use tables similar to Tables 5, 7, and 8 to rate KIF and convert to qualitative values of High (H), Moderate (M), and Low (L).
Confirmatory Karst Criteria: Plot known caves (C), major surface karst features (K), and areas of cave/karst inspections (I) on separate GIS layers. Determine the density of caves, major surface karst features, and inspections. Convert to qualitative ratings of Low (L), Moderate (M), and High (H).
Final Product: Reconnaissance level map at 1:250 000 scale with carbonate polygon outlined and rated for:
Criterion 1 (P, S, and T)
Criterion 2 (H, M, and L)
Confirmatory Criteria (C_x, K_x, I_x, where x = low (l), moderate (m), or high (h)
For Example: Polygon has a primary criterion 1, low criterion 2, low cave density, low major surface karst feature density, and low inspection density.
Karst polygon
P, L
(C, K, I)

FIGURE 4 *Proposed reconnaissance-level KISP methodology.*

estimate. Typically, this might be in terms of a qualitative description (e.g., trace, minor, some, or major component). A preferable estimation would be as a percentage volume of a particular unit. It would be useful if some indication was given as to the reliability of this estimation. Table 4 provides a general guide that could be used for this purpose. It is suggested that the terms primary (P), secondary (S), and tertiary (T) be used as a qualitative rating system for this criterion. The terms primary, secondary, and tertiary are used to clearly signify the relative importance of the karst-bearing units.

TABLE 4 *The likelihood for karst-forming bedrock to occur within a geological unit (for use at a mapping scale of 1:250 000)*

Verbal estimate of karst-forming bedrock in geological unit	% estimate of karst-forming bedrock in geological unit	Qualitative rating
Major, Significant	50–100%	HIGH
Some	25–50%	MODERATE
Minor, Small	10–25%	LOW
Trace	<10%	NEGLIGIBLE OR VERY LOW

Criterion 2 Determination - Intensity of karst development In order to obtain a general idea of the potential intensity of karst development within a particular type of karst-forming bedrock, it is necessary to obtain some fundamental bedrock information on lithology type (purity/form), unit thickness, and structural setting. Bedrock lithology considers the closely related features of bedrock type (e.g., calcareous dolomite), form (e.g., massive, thick bedded, thin bedded, or interbedded), and purity (% $CaCo_3$).[6] The first two features are typically present on map legends and in associated publications. In some places, these limestone rocks have undergone geochemical analysis so that quite accurate data on purity are available. An estimate of the stratigraphic thickness of a unit provides an indication of the amount of bedrock that is available for karst processes to work on; the greater the thickness, the more karst development that might be anticipated. Regional structural/tectonic settings can be used to provide some indication of the intensity of structural disturbance within a particular unit. This can be very approximately correlated to the amount of uplift, folding, faulting, and fracturing that might be anticipated. The greater the amount of structural disturbance, the greater the intensity of karst development (see Table 8). The above information is available from a variety of sources, such as geologists familiar with an area and government publications/open files/maps.

[6] In many cases, carbonate purity is reported in chemical analysis as %CaO (e.g., Fischl 1992). This can easily be converted to $\%CaCO_3$ multiplying by a factor of 1.78.

Following information gathering, an analysis can be completed for a particular karst-forming unit using a numerical rating scheme and a suitable algorithm that combines all the attributes. Development of an acceptable set of tables and an algorithm will require further verification in a variety of carefully selected areas of British Columbia (e.g., Vancouver Island, Nelson, Prince George). For the purposes of discussion, a series of tables has been developed to outline the proposed methodology (see Tables 5 to 8). These tables have been completed for bedrock lithology, unit thickness, regional topographic position, and structural setting. Weightings for the subcategories of the attributes were provided directly into the tables. Details for climatic setting, topographic setting, vegetation, and soil cover could be obtained from the 1:250 000 biogeoclimatic maps of British Columbia. Further work is required to develop a numerical rating scheme for each of the biogeoclimatic units at the subzonal or zonal level, and to incorporate these data into the algorithm below.

In developing a suitable algorithm, bedrock lithology, topographic position, and unit thickness were considered the primary controls on karstification. The algorithm proposed, and the attributes taken into account, are as follows:

Karst Intensity Factor = [BL + TP + UT + tss + vc + sc + cs]

BL – Bedrock Lithology	**tss – tectonic/structural setting**
TP – Topographic Position	**vc – vegetation cover**
UT – Unit Thickness	**sc – soil cover**
	cs – climatic setting

By using this methodology, it should be possible to come up with a range of numerical values for the various karst-bearing units in British Columbia. These can then be converted into qualitative ratings for allocation to the appropriate polygons. It is suggested that the terms High (H), Moderate (M), and Low (L) be used to indicate the relative intensity of karst development.

Suggestion 3. An algorithm combining the main karst-forming attributes of bedrock lithology (BL), topographic position (TP), unit thickness (UT), tectonic/structural setting (tss), vegetation cover (vc), soil cover (sc), and climatic setting (cs) is proposed. It will provide an estimate of karst development or intensity for a particular bedrock unit.

If it is found that the general algorithm for the Karst Intensity Factor is too complex, it could be simplified to include only bedrock lithology, topographic position, and unit thickness as follows:

Karst Intensity Factor (Simple) = [BL + TP + UT]

TABLE 5 *Suggested karstification rating values based on bedrock lithology types (suitable for mapping at 1:250,000 scale)*

Lithology	Number rating	Comments
Massive, thick, or medium bedded limestone (>70% pure)	10	Most limestone units with a purity of greater than 70% limestone will develop good karst.
Thin bedded limestone (>70% pure)	9	Bedding planes play an important role in directing solutional networks.
Interbedded limestone with other sediments/volcanics	8	In many cases, interbedded limestone units can develop good conduit systems, but they are poorly connected between limestone beds.
Interbedded limestone with other	6	sediments/volcanics (<60%, but >20% limestone beds).
Interbedded limestone with other sediments/volcanics	3	(<20% limestone beds).
Argillaceous limestone (<20–30% clays)	5	Clay materials within limestone reduce the karstification process, potentially clogging channels.
Argillaceous limestone (>20–30% clays)	1	
Calcareous sandstone (<50% carbonates)	2	Extensive karst does not develop in this lithology, but it can form some features (dolines/caves).
Calcareous mudstone/siltstone (<50% carbonates)	0	Little karst development is anticipated.
Marble (metamorphosed limestone or dolomite)	7	In most cases, marble has a low porosity with negligible permeability, but most marble is jointed/faulted and can provide conduits for dissolution.
Dolomite	7	
Calcareous dolomite	8	
Dolomitic limestone	8	
Gypsum/Anhydrite	10	
Halite	10	

TABLE 6
Suggested karstification values related to unit thickness and ability to develop water circulation systems

Unit thickness (may or may not include non-karst bedrock)	Number rating	Comments
Thin (0–5 m)	1	Likely small, confined, and incomplete circulation systems.
Medium (5–20 m)	2	Small circulation systems with irregular water recharge and discharge.
Thick (20–100 m)	4	Moderate-size circulation systems with likely regular recharge and discharge.
Very Thick (>100 m)	10	Large circulation systems with complete recharge and discharge systems.

TABLE 7
Suggested karstification values based on regional topographic setting (suitable for mapping at 1:250 000 scale)

Regional topographic setting	Number rating	Comments
Upper elevation or peak areas of mountain ranges	5	In most cases, these areas occur at upper alpine/subalpine elevations. Significant hydrological head present. Excellent conditions for karst processes, providing that reasonable precipitation conditions are present.
Mid and upper slopes of mountain ranges	4	Variable soil thickness cover, but well-developed hydraulic heads. Good conditions for karst processes.
Raised plateaus	3	Can be laterally extensive, but likely to have deeper water table from ground surface than valley bottoms.
Lower slopes and valley bottoms	2	Thick surficial cover and water table near to ground surface, less hydrological circulation. Limited potential for karst processes.
Coastal flat or along shoreline	1	Relatively high water tables and less water circulation; exceptions would be where steep and high terrain occurs immediately on shore.

TABLE 8
Suggested karstification values based on regional structural setting (suitable for mapping at 1:250 000 scale)

Regional structural setting	Number rating	Comments
Subhorizonal or gently (<10°) dipping	1	In most cases, these areas would have undergone minor regional folding and faulting (thrust environments).
Moderately dipping (>10° to <30°)	2	Likely to have undergone some uplift, less faulting/fracturing than steeply dipping.
Steeply dipping (>30° to <60°)	3	Likely to have undergone significant uplift during folding and faulting.
Subvertical (>60°)	4	Likely in areas where extensive folding and faulting has occurred. Faults could be a major control on karst conduits.

3.2.3 Cave areas, major surface karst features, and inspection level confirmation criteria

Information about known cave areas and major surface karst features is useful in confirming that some level of karst development is present within a particular karst-forming unit. It could be particularly useful for verification purposes, especially in areas where limited geological information is available. However, these criteria are a function of the level of assessment/inspection of a particular karst-forming unit, and should not be considered factors that control karst processes. It is suggested that the three confirmation criteria—known cave areas, known major surface karst features, and inspection level—be treated and used differently from Criteria 1 and 2. It should be understood that these three confirmatory criteria may change with time as more cave areas and surface karst features are encountered. Information sources for these data could be obtained from existing karst inventory reports, local recreational cavers, and other industry or government files.

Other sources of information that could be used to confirm the presence of surface karst features include high-level airphotos and digital data from remote sensing satellites (e.g., infra-red, radar imagery; [Nossin 1989; Glasco 1992]). Only the largest individual karst landform features are discernable from space. Landsat MSS images, for example, provide a relatively coarse resolution of about 80 metres. However, patterns and textures associated with solution morphology in karst landscapes are discernable. Karst areas can exhibit a relatively homogeneous "pock-marked" texture when viewed in space images. The absence of a well-developed integrated surface drainage network is another reliable karst "signature." A series of commercial satellite launches is planned in the near future that will permit resolution approaching that used by military surveillance satellites. These kinds of images could prove useful in future karst inventory work.

Known cave areas with given geographic reference points could be incorporated into a suitable GIS layer, and overlain onto the polygons of karst-bearing units. Obvious issues related to security would have to be considered with the development of such a layer, and suitable precautions would be needed to ensure that the data were stored and used correctly. Possible methods for providing some level of security would be to use geographic reference points accurate to the nearest 250 m (or 1 mm on a 1:250 000 map). Cave areas would be used rather than specific cave entrances, because one cave system might have numerous entrances. By using the spatial distribution of known caves and the area of a particular karst-unit polygon, it should be relatively easy to come up with an approximate value for known cave density. Numerical ranges for cave density could be obtained and converted to a suitable qualitative rating system (e.g., high, moderate, or low density of known cave areas).

Details of known major surface karst features could be obtained and analyzed in a similar fashion to cave areas to give a qualitative density rating for these features. A separate GIS layer with point data could be compiled for this information. Typically, the types of major or macro surface karst features considered would include disappearing creeks/insurgences, significant sinkhole/grike areas, rock bridges, extensive

epikarst pavements, and discharge areas. Minor or micro surface karst features would not be considered.

A qualitative rating based on the level of cave/karst inspections would also be useful to provide an indication of the amount of local knowledge of caves or major surface karst features in an area. Typically, this knowledge is gained from a combination of recreational cave visits/exploration of areas, cave/karst inventories completed for forest districts or the forest industry, and other research studies. This information could be incorporated into a separate GIS layer as either point or, more preferably, polygon data, so that an approximate percent coverage value could be obtained.

Suggestion 4. Known cave areas, major surface karst features, and the level of cave/karst inspections should be used as criteria to confirm the presence of karst areas. Maps of these three confirmation criteria can be overlain onto maps containing polygons labelled with Criteria 1 and 2.

3.3 Suggested Standards for Mapping, Data Representation, and Data Reliability

The reconnaissance-level karst inventory is primarily intended to be an office study. Field reconnaissance could be carried out, and in some cases might be recommended, to evaluate type localities of a karst-bearing unit or where few or no data are available for a unit. This type of reconnaissance could include ground work at carefully selected sites or aerial viewing. Data that could be obtained from a general field examination of a potential karst-bearing unit are: i) the proportion of carbonate within a unit (for Criterion 1), ii) the probable thickness of a unit, iii) the presence of major surface karst features, and iv) the structural setting. Representative samples of material could also be obtained for geochemical analysis of carbonate content.

Data representation for reconnaissance inventory maps should follow the mapping methodologies laid out in Part 3 of the SGBM-BC, pp. 13–23. That section provides useful information for title blocks, base map specifications, legends, map attributes, symbols, and rock terminology. Some adaptation will be required. Each karst-bearing polygon could be assigned a combination of symbols for Criterion 1 (P, S, T) and Criterion 2 (H, M, L). These maps could be overlain with maps derived from the confirmation criteria: known cave area density (C), surface karst feature density (K), and inspection coverage (I). See Figure 4 for an example.

It is recommended that short reports accompany the various projects that are completed for collecting reconnaissance information. They would detail any specific methodology, project limitations, sources of information, references, and a list of contacts.

It is recommended that the reconnaissance karst inventory work be completed by professional geoscientists familiar with karst processes and digital GIS mapping techniques.

Data reliability for this scale of inventory is primarily a function of the information available. Where possible, recognized government publications and maps should be used. Information from other sources, such as industry or consultants, should be carefully documented and referenced.

3.4 Management Implications

Reconnaissance karst inventories are critical for the long-term management of forest and karst resources, and provide a source of information for strategic planning. In addition, they can be used to flag critical areas, which may assist planners by highlighting areas where development costs might be higher. For example, it should be possible to examine a large watershed (or group of watersheds) from the reconnaissance inventory map and infer the likelihood of both encountering karst (Criterion 1) and the probable intensity of karst development (Criterion 2). These inventories will also provide baseline information for the other more detailed planning- and operational-level karst inventories. Potential end-users of the reconnaissance inventory maps and data would likely include not only forest licensees and the B.C. Ministry of Forests, but also fishery and wildlife workers, archeologists, paleontologists, First Nations, recreational cavers, mineral explorationists, and the tourism industry.

Costs for these inventories are anticipated to be relatively low, because much of the procedures are office-based. In addition, much of the required information, such as the digital bedrock data, is already available in a user-friendly format. The amount of karst and the level of knowledge of known cave areas and karst features will play a major role in determining project costs. For example, a project for Vancouver Island (with its extensive areas of karst that have undergone considerable investigation) will likely be more expensive than for the mid-coast where little karst is known and limited information is available. Estimates based on budgets prepared for a 1997 Forest Renewal BC (FRBC) proposal suggest possible average costs of $200–300 per 1:250 000 NTS map sheet.

4.0 PROPOSED PLANNING-LEVEL KISP (1:50 000 to 1:20 000 MAP SCALES)

4.1 Objectives and Approach

This section outlines the suggested methodologies for the planning-level karst inventory. These methodologies could require some adaptation, depending on the level of existing karst inventory information available in various forest regions and districts. If existing karst information is available in a suitable format, it could simply require refinement and updating to raise the information to an acceptable standard.

The aim of the planning-level karst inventory is to provide a management tool that can be used for detailed forest development planning at the landscape scale. In comparison with the reconnaissance-level karst inventory, this level is an intermediate filter in which more specific attributes controlling karst development are examined. The primary objectives of the planning-level inventory are to further delineate the boundaries and three-dimensional character of the karst units, examine the regional extent of catchment and recharge areas, identify subsurface groundwater paths, and obtain an indication of the intensity and distribution of surface and subsurface karst development.

Three phases are proposed for the planning level karst inventory (see Figure 5). These adapt two existing inventory/mapping methodologies and introduce a third. Phase 1 would use the current L5 recreation polygon data as base information to assist in delineating the boundaries of karst-bearing units and potential recharge/catchment areas. This could be done

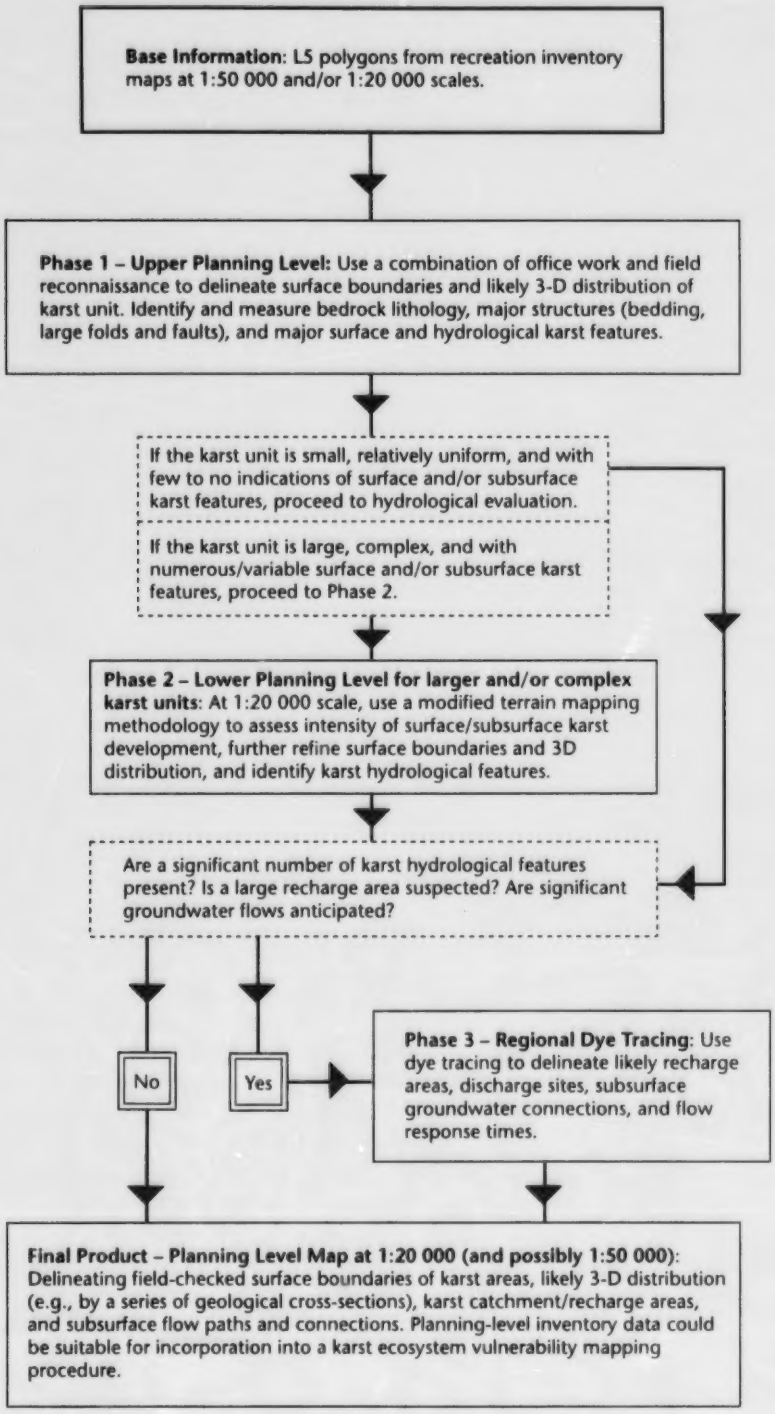

Base Information: LS polygons from recreation inventory maps at 1:50 000 and/or 1:20 000 scales.
Phase 1 – Upper Planning Level: Use a combination of office work and field reconnaissance to delineate surface boundaries and likely 3-D distribution of karst unit. Identify and measure bedrock lithology, major structures (bedding, large folds and faults), and major surface and hydrological karst features.
If the karst unit is small, relatively uniform, and with few to no indications of surface and/or subsurface karst features, proceed to hydrological evaluation.
If the karst unit is large, complex, and with numerous/variable surface and/or subsurface karst features, proceed to Phase 2.
Phase 2 – Lower Planning Level for larger and/or complex karst units: At 1:20 000 scale, use a modified terrain mapping methodology to assess intensity of surface/subsurface karst development, further refine surface boundaries and 3D distribution, and identify karst hydrological features.
Are a significant number of karst hydrological features present? Is a large recharge area suspected? Are significant groundwater flows anticipated?
No
Yes
Phase 3 – Regional Dye Tracing: Use dye tracing to delineate likely recharge areas, discharge sites, subsurface groundwater connections, and flow response times.
Final Product – Planning Level Map at 1:20 000 (and possibly 1:50 000): Delineating field-checked surface boundaries of karst areas, likely 3-D distribution (e.g., by a series of geological cross-sections), karst catchment/recharge areas, and subsurface flow paths and connections. Planning-level inventory data could be suitable for incorporation into a karst ecosystem vulnerability mapping procedure.

FIGURE 5 *Proposed planning-level KISP methodology.*

at a scale of 1:50 000 (or possibly 1:20 000) and be considered an upper planning level. Phase 2 is a refinement of the terrain mapping methodology, and concentrates on further delineating the boundaries of the karst-bearing units and assessing the intensity of surface/subsurface karst development. This mapping should be carried out at a scale of 1:20 000 and is considered a lower planning level. Phase 3 introduces regional dye tracing to delineate recharge and discharge areas, and likely paths for major groundwater flow.

In terms of timing, Phases 1 and 2 could be done sequentially or concurrently. Phase 3 should be completed after Phases 1 and 2, because much of the information obtained in the earlier phases will be needed (e.g., locations of swallets for dye injection sites and springs for dye samplers). However, the need to complete Phases 2 and 3 will also depend on the size and complexity of the karst unit. A large, complex karst unit with variable surface karst characteristics and numerous subsurface openings and hydrological features (e.g., swallets and springs) would probably require Phase 1 followed by Phases 2 and 3. A small, uniform karst area with no subsurface indicators or hydrological features might require only Phase 1. The advantages of completing Phase 1 at a 1:50 000 scale are that it is usually the scale of base information (e.g., bedrock geology), and it would be possible to view large contiguous karst-bearing units and catchment areas on one map.

Suggestion 5. Three phases are proposed for the planning level karst inventory. Phase 1 uses L5 recreation polygons at 1:50 000 or 1:20 000 scales to delineate the boundaries of karst units. Phase 2 uses modified terrain mapping methods at a 1:20 000 scale to delineate the intensity of surface/subsurface karst development. Phase 3 uses regional dye tracing to delineate recharge and discharge areas, and likely paths for major groundwater flow.

4.2 Phase 1 - Upper Planning Level Methodology

The general objectives of Phase 1, the upper planning level inventory, are:

- to delineate the surface boundaries of the karst unit,
- to determine the likely subsurface, three-dimensional distribution of the karst unit and its relationship to major structural features (e.g., bedding, major faults and folds) and adjacent bedrock units,
- to determine any variations in lithology of the karst unit (e.g., interbedding),
- to recognize major surface karst areas/features (e.g., cave entrances, areas of extensive epikarst, large sinkholes, sinking or reappearing streams), and
- to determine, where possible, the potential extent of both karst and non-karst catchments.

This procedure could primarily be carried out in the office, but does require some reconnaissance field work. A digital base map at a scale of 1:50 000 should be compiled from available digital TRIM data and incorporated into a suitable GIS system. This base map should include coastline, creeks, lakes, topography, and major roads.

Suggestion 6. The objectives of Phase 1, the upper planning level inventory, are to delineate the surface boundaries and three-dimensional distribution of a karst unit, determine lithological variations within the karst unit, and recognize any major surface karst areas/features. This work should be carried out through a combination of office study and field reconnaissance.

4.2.1 Office work and project initiation

Recreation L5 polygon data, along with detailed (1:50 000 scale or larger) bedrock maps and 1:50 000 terrain/surficial geological maps, should be obtained for the area and used as base information. A determination of how the L5 polygon data were compiled (e.g., office work using bedrock geology maps or some reconnaissance field work) should be made. If the data are considered geologically reliable and accurate (e.g., L5 polygon boundaries approximately match that of bedrock mapping and some field work has been done to check the karst limits), they could be compiled as a separate base layer into the GIS system defining the boundaries of karst-bearing units. If many other recreation features are included in the L5 polygons, it may be better to use the bedrock geological map as the base information. If only regional-scale bedrock mapping is available, karst information from 1:50 000 terrain mapping could be considered for base information.

An index of all bedrock mapping completed for British Columbia is available over the Internet from the British Columbia Geological Survey Branch (BCGSB) at **http://www.em.gov.bc.ca/geology/** (follow links to downloadable mineral potential files) and also in hardcopy (BCGSB Information Circular 1991-7). Most of these detailed maps have been completed by British Columbia government geologists, particularly in areas of mineral potential or mining interest. Bedrock mapping at 1:50 000 scale is not available for all parts of British Columbia, although some form of old, detailed mapping is usually available (e.g., 1:64 000, 1 inch to 1 mile). The remote northern parts of British Columbia typically do not have mapping at these more detailed scales, and may require the use of regional-scale (e.g., 1:250 000 or 1:100 000) maps. The boundaries of karst units from the regional (1:250 000) digital bedrock maps of British Columbia (see Section 3.0) were compiled at a 1:100 000 scale, and could be considered only a very approximate guide at the 1:50 000 scale. The information sources for the 1:250 000 scale compilations should be examined to see if areas of interest have been mapped in detail.

During the late 1970s and early 1980s, the Ministry of Environment produced terrain/surficial geological maps at a 1:50 000 scale for most parts of southern and central British Columbia. An index for these maps is available over the Internet from the BCGSB at **http://www.em.gov.bc.ca/geology/** or in hard copy (BCGSB Open File 1992-13). Where present, as required by the Terrain Classification System of British Columbia, karst is identified on terrain maps as a process modifier (-K). However, experience from Vancouver Island has shown that this process modifier has not always been used.

From experience, it is anticipated that the boundaries of karst-bearing units determined from bedrock mapping will probably be more accurate than those determined from terrain mapping. The reason behind this is that former mapping procedures focused specifically on bedrock relationships, while the latter concentrate on surficial materials overlying bedrock. With this in mind, it is suggested that these boundaries be kept as separate layers within the GIS, or be given different colours/linings until confirmed by field reconnaissance. In some areas, terrain mapping may be the only source of detailed mapping that has been completed, and hence could be more reliable than regional-scale bedrock maps.

High-level airphotos (e.g., >1:50 000) or remote-sensing maps could be used to assist in determining the boundaries of karst-bearing units, particularly if a distinct visual terrain attribute (e.g., vegetation change) is present. Sparsely vegetated or logged areas are likely to show karst features and terrain more readily.

4.2.2 Field work

In order to determine the general objectives of Phase 1, reconnaissance field work should be carried out using the most readily accessible sites where karst-bearing bedrock might be encountered (e.g., road cuts, exposures in logged cutblocks, and creek channels/sidewalls). In more remote areas, accessible only by air, traverses could be carried out with the intention of intersecting as much karst bedrock as possible.

In some cases, where recent 1:50 000 bedrock maps have been compiled and completed to RIC requirements (e.g., 1000 stations/1:50 000 NTS map sheet), the need to confirm the boundaries of the karst-bearing units may be low. Nevertheless, information would still be required on the general characteristics and major features of the karst unit. Confirmation of some boundaries could be carried out using maps from previous karst inventory reports. The karst inventory attributes that should be identified during the completion of Phase 1 are highlighted in Table 9 by a single asterisk.

From the distribution of bedrock exposure and bedrock contact relationships, it should be possible to develop final map boundaries for karst-bearing units. These boundaries can be indicated as defined, approximate, or inferred, according to standard bedrock map symbols (SGBM-BC, p. 21). The location, identification, and measurement of any major surface karst features encountered will assist in determining both the overall extent and intensity of karstification. Surface hydrological karst features, combined with a knowledge of the topographic catchment areas and the distribution of nearby karst units, should enable educated speculation on likely recharge and discharge areas. Recharge areas from some non-karst units could also be identified. Thus, a preliminary indication of the overall non-karst and karst catchments might be obtained from a relatively simple mapping exercise, and potential areas of hydrological concern could be identified for later investigation (e.g., provide a focus for Phase 3 work).

Regional geological cross-sections could be drawn using available topographical, lithological, and structural data. This will assist in determining the three-dimensional distribution of the karst units. Preliminary examinations of the karst hydrological system can be carried out to determine likely groundwater flow paths and discharge/recharge

TABLE 9 *Surface karst attributes and features*

Karst attribute or feature	Data measurements/requirements
	Geological and Geomorphological
Karst unit lithology*	Form (e.g., massive, thin bedded, interbedded), type (e.g., limestone, dolomite), purity (e.g., colour, chemistry)
Adjacent lithology*	Types and contact relationships with karst unit (e.g., faulted, gradational, intrusive)
Thickness of unit*	Measured from outcrop or inferred over a series of outcrops
Extent of karst unit exposed in outcrop*	Mapped using standard convention (dotted line or x)
Bedding planes*	Strike direction/dip direction
Major faults*	Fault plane strike dip, offset, slickensides
Major folds*	Fold axis, axial plane, size
Minor faults**	Fault plane strike/dip, offset, slickensides
Minor folds**	Axial plane - strike/dip, fold axis - plunge, shape, size)
Joints**	Sets, orientation, spacing, openness
General topography*	Slope gradients; mid, upper or lower slopes; benched, uniform
Detailed topographic form/character**	Concave, irregular, uniform, straight
Surficial materials**	Type (e.g., moraine, fluvial, colluvium), thickness (e.g., thin veneer, veneer <1 m, blanket >1 m, or mantle), weathering depth, drainage (e.g., well drained, poorly drained, imperfectly drained)
Forest floor/organic layer**	Type, depth to mineral soil
Major sinkholes or closed depressions*	Diameter, shape, depth, openness
Cave entrances**	Size (width, height)
Shaft or Karst Window**	Size and depth, presence/absence of water at base
Grykes**	Size (width, height, length, openness)
Natural rock bridges**	Size (width, height, length)
Canyons**	Size (width, height, length)
Cliffs**	Height, length
Surface epikarst development**	Depth of solutional openings, percentage of area/exposed bedrock, openness
Microkarst features	Karren, percentage of exposed bedrock
	Hydrological
Topographic catchment*	Size, area, boundaries
Karst recharge (including non-karst areas)***	Size, boundaries (possible, probable, definite)
Dry channels/valleys**	Length, gradient, sidewall slope
Seepages/springs**	Elevation, flow rate, temperature, pH, conductivity, oxygen content

TABLE 9 *(Continued)*

Karst attribute or feature	Data measurements/requirements
Insurgence (swallet)**	Elevation, flow rate, temperature, pH, conductivity
Disappearing streams**	Elevation, flow rate, temperature, pH, transport capability for sediment and woody debris
Diffuse and discrete recharge areas**	Size and distribution (e.g., infiltration or percolation zones)
Lakes and ponds*	Size, water inputs and outputs
Wetlands/swamps*	Size, water inputs and outputs
Surface overflow channels**	Channel width and height, transport capability for sediment and woody debris
	Natural Disturbances
Fire/burn areas**	Extent, intensity
Tree windthrow**	Orientation, age, amount
Landslides**	Location, size, materials
Rockfall and soil slumps**	Location, size, materials
Gully sidewall/channel erosion**	Location, size, materials
Surface flooding**	Level, size, frequency
	Karst Flora and Fauna
Rare or unique plants and plant communities**	Species, location
Rare or endangered surface karst fauna or habitats**	Species, location
Cave entrance habitat**	Type and conditions
	Climate and Air
Slope aspect**	Azimuth
Precipitation	Estimates of maximum, minimum, mean
Air temperature around surface karst features or depressions	Estimates of maximum, minimum, mean
Snow depth	Estimates of maximum, minimum, mean
Surface evapotranspiration	Estimates of maximum, minimum, mean

* denotes data collection possible during Phase 1 of the planning-level inventory,
** denotes collection possible during Phase 2 of the planning-level inventory,
*** denotes collection possible during Phase 3 of the planning-level inventory.
All attributes listed in the table should be collected if possible during the operational-level inventory.

sites. This information could be critical to the dye tracing procedures of Phase 3. Further modification of these cross-sections can be carried out following the more detailed assessments of Phase 2.

4.3 Phase 2 - Lower Planning Level Methodology

The primary objectives of Phase 2, the lower planning level, are:

- to assess the intensity of surface/subsurface karst development within the karst unit,
- to further refine the three-dimensional distribution of the karst unit,
- to identify further hydrological karst features suitable for Phase 3, and
- to identify, in a preliminary manner, the likely presence of any unique karst-specific biota or related habitat.

For the purposes of a lower planning level karst inventory, it is suggested that the guidelines and standards for terrain mapping at a 1:20 000 scale be followed, but that some adjustments and refinements be added for karst. The information gathered during terrain mapping focuses on data similar to those required for a karst inventory, including surficial cover type/thickness, geomorphic processes present, surface expression/topography, and specific features/on-site symbols. However, various items require modification to take into account variability in karst features and karst hydrology. Information from this mapping could then be relatively easily incorporated into a planning-level karst vulnerability rating system (see Section 6.0), providing that the appropriate data have been collected. This karst vulnerability map would then become a derivative terrain map, in a similar fashion to a slope stability hazard map.

Suggestion 7. The objectives of Phase 2, the lower planning level inventory, are to assess the intensity of surface/subsurface karst development within a karst unit, further refine the unit's three-dimensional distribution, and identify surface karst features suitable for dye tracing. This work is carried out mainly by terrain mapping with some modifications for karst purposes.

Methodologies for terrain mapping within forested areas of British Columbia are well outlined in the FPC *Mapping and Assessing Terrain Stability Guidebook*, the GSTM-BC, and the TCS-BC. Standards for digital terrain data usage are included in the TDM-BC. A summary of particular references to karst in the above publications is included in Section 2.0.

One point that must be emphasized is that terrain mapping, modified for lower planning level karst inventories, cannot alone assess the three-dimensional nature of karst. It can provide only some indication of the likely subsurface characteristics. However, in combination with additional attributes (e.g., bedrock structure) and regional dye tracing in Phase 3, it should be able to provide a relatively good idea of the distribution and intensity of overall karst development.

In practice, 1:20 000 terrain mapping may or may not have been completed for the area of interest for a karst inventory. Three possible scenarios are likely: i) no terrain mapping has been done; ii) terrain

mapping has been done, but to a relatively low survey intensity level and before the existing standards; and iii) terrain mapping has been done to an acceptable standard (e.g., GSTM-BC) and survey intensity. In the first case, terrain mapping for the karst inventory area should be carried out, but would be limited by the approximate boundaries of the karst unit obtained in Phase 1. If possible, terrain mapping for the karst inventory could be done concurrently with prescribed slope stability or terrestrial ecosystem mapping. In the second case, some improvement to terrain mapping may be required, but it should be possible to use this as a base map for the karst inventory. In the third case, the terrain mapping could be used as the base map with karst details superimposed. In some circumstances where terrain mapping has been done and previous karst inventory work has been completed, this might be primarily an information transfer process.

4.3.1 Office work and project initiation

In addition to gathering the standard information required for a terrain mapping project (e.g., surfical geology maps, bedrock maps, airphotos, and other terrain maps/publications), the planning-level inventory would require the collation of any karst-related information. This could include karst inventory maps, cave maps, related publications, and input from local interest parties (e.g., cavers, B.C. Ministry of Forests recreation officers). Other useful information could be gathered from forest cover maps, forest development plans, terrestrial ecosystem maps, and fish inventory maps. Local offices of BC Environment could be contacted to determine if any karst-related biota (e.g., threatened or endangered wildlife or plants) occur within the area of interest. A working base topographic map (from TRIM data) should be compiled with coastlines, streams, lakes, and roads. A suitable set of airphotos should be chosen prior to the field work (see Sections 5 and 6 of the GSTM-BC). These airphotos should be pre-typed for terrain polygons, but should also focus on karst processes, using any additional information where required.

4.3.2 Modification of terrain attribute symbols for terrain mapping polygons

Polygons are used for terrain mapping to outline an area with relatively uniform criteria of surfical material texture/type, landform type, and processes. In some cases, these polygons are simple (no more than one element per criterion), while in others they are composite (two or three elements per criterion). However, whether the polygons are simple or composite, they can still define a homogeneous area with respect to adjacent polygons. Details on polygon definitions, boundaries, etc. are included in Section 4.0 of the GSTM-BC.

Terrain mapping polygons could be made suitable for karst inventory purposes by using a descriptive "subclass code" table for the karst (-K) process. A proposed table for this purpose is illustrated in Table 10. This table could possibly be revised to incorporate indications of subsurface karst development as well. Similar tables have been completed for mass movement, avalanche, fluvial, and permafrost processes (see Tables 12–14 in the TDM-BC).

It is also suggested that additions be made to the terrain symbol list (Appendix I of the GSTM-BC) to accommodate more karst features. These could be adapted from existing karst mapping symbol standards. Features that could be included, along with existing cave entrances and large and small sinkholes, are: dry valleys, large stream insurgences, major stream exsurgences, karst bridges, karst canyons, karst springs or group of karst springs, and major grikes. Table 11 outlines examples of proposed symbols that could be added. The table is constructed in a format compatible with Appendix I of the GSTM-BC.

TABLE 10 *Suggested subclasses for karst process modifiers for British Columbia terrain classification system*

Code	Subclass name	Definitions
i	intensely developed epikarst	Ridges/peaks and depressions, extensive development of micro-karst features (e.g., karren and runnels) on numerous exposed bedrock surfaces. Occasional sinkholes and cave entrances/shafts. Average openings to >10 m. Probably visible on airphoto with distinct vegetation change or lack of well-developed vegetation.
g	gryke field	Area of well-developed epikarst with linear grykes linking depressions, development of micro-karst features on bedrock exposures, most sinkholes open at depth, >5–10 m average depth.
e	well-developed surface epikarst	Ridges and depressions with micro-karst features developed on ridge tops, depressions closed at depth and infilled with forest floor/surficial material. >2 to < 5 m average depth.
s	sinkhole field	Numerous sinkholes encountered <50 m average spacing between centres, with occasional bedrock exposures with minor micro-karst. >2 to <5 m average depth.
t	occasional sinkholes	Occasional sinkholes >50 m spacing with few bedrock exposures, and evidence of micro-features on minor exposed bedrock. <2 m average depth.
r	rare sinkholes	Few sinkholes >100 m spacing, traces to no areas of exposed bedrock or micro-karst features. <2 m average depth.
n	insurgence sites	Area where a number of small creeks disappear either into surface epikarst or sinkholes. Too small to map as single-symbol features.
x	exsurgence sites	Area where a number of small seepages/creeks reappear. Too small to map as single-symbol features.

TABLE 11 *Suggested additional terrain mapping symbols for karst features*

Group: Geomorphologic

Symbol description	Symbol	Positional definition	Definition/remarks
Dry valley		accurate to within 50 m	Linear gully with overflow channels and possible sinkholes
Stream insurgence		feature at centre of symbol	Single major stream flow that abruptly disappears
Stream exsurgence		feature at centre of symbol	Single major stream flow that abruptly appears
Natural karst bridge		feature at centre of symbol	Large arch spanning canyon
Karst canyon/gorge		accurate to within 50 m	Linear gully with subvertical bedrock sidewalls
Karst spring		feature at centre of symbol	Single spring from karst unit
Karst spring group		group at centre of symbol	Series of springs from karst unit
Major gryke		accurate to within 50 m	Linear depressions open at depth

Bedrock classification codes are also present in the terrain mapping system and could be utilized to identify variations in bedrock type. A system of suffixes could be added to bedrock codes to identify local variations in bedrock lithology. This could be done on an informal or local basis and should be acceptable, providing the details are well laid out in legends and text. For example, limestone "ls" could be suffixed as: ls_1 for massive limestones, ls_2 for massive well-bedded limestone, ls_3 for thin-bedded limestone, and ls_4 for interbedded limestone.

Suggestion 8. Modify the existing Terrain Classification System of British Columbia with more details for karst process descriptors/subclass codes, karst terrain symbols, and bedrock classification codes. This will assist in the modification of terrain mapping methodology for planning-level karst inventories.

4.3.3 Attributes for Phase 2

At 1:20 000 scale, a variety of karst geological, geomorphological, and hydrological attributes can be identified and measured during the Phase 2 terrain mapping field work. These attributes are highlighted in Table 9 by a double asterisk. General observations should be made with respect to any anomalous/unusual karst-associated surface flora or fauna. If such biota are encountered, the information should be relayed to other appropriate inventory specialists for further assessment.

4.3.4 Field work procedures

Field work for Phase 2 is anticipated to be similar to any other terrain mapping project and should follow the general details laid out in Section 7.0 of the GSTM-BC. These details include careful use of time, a pre-project regional reconnaissance, designated observation sites/traverses, and polygon field typing. The level of field checking required for a mapping project can be defined in terms of the Terrain Survey Intensity Level (TSIL), which provides an indication for the percentage of terrain polygons checked or the number of field checks per 100 ha (see Table 7 in GSTM-BC). The TSIL level used for a mapping project is typically a function of terrain and vegetation conditions, and the anticipated use for the terrain map. In the case of a karst inventory, particularly in forested areas, the mapping should be carried out at least to TSIL C, with 25–50% of polygons field checked. If the karst area is complex and/or it is anticipated that the data will be used subsequently for vulnerability mapping, TSIL B (50–75% of polygons field checked) or possibly TSIL A (75–100% of polygons field checked) may be required.

4.4 Phase 3 - Regional Dye Tracing

One of the unique characteristics of karst terrain is its different hydrological system compared to non-karst terrain. Most of the karst hydrological system is subsurface, with recharge areas that not only do not follow topographic divides, but in many cases, cross them. Likewise, subsurface drainage may not follow simple paths, and exsurgenences (e.g., springs) can occur in unexpected places. Groundwater systems within karst have the potential to both rapidly transmit flows through bedrock conduits, and to provide groundwater storage in permeable, fissured bedrock volumes (e.g., in epikarst areas). Hence, karst hydrological systems can be characterized as highly variable and difficult to predict from surface features. Any evaluation of these hydrological systems needs to consider differences in stage height (i.e., flow regime), because discharge directions and groundwater divides in karst can vary according to how much water is present in the system. In some cases, it may be necessary to assess karst hydrological systems under different discharge conditions. Dye tracing is a well-accepted methodology for evaluating karst hydrological systems, and can be used successfully to delineate recharge areas, assess groundwater flow paths, and identify discharge sites (Aley and Aley 1993; Gunn 1995; Doerfliger 1996).

Dye tracing is undertaken using a fluorescent dye injected into a recharge site (e.g., sinking stream), which is then tracked by sampler sites located at likely discharge locations (e.g., springs). Examples of dye tracing methods, materials and analytical procedures are provided in Appendix 1.

One of the principal concerns in karst hydrology is the transport of materials from a site of management activity to an area downstream where other resources may be affected. The materials that can typically be generated during forest development activities include sediment, logging debris, and pollutants (e.g., diesel fuel). In non-karst terrain, various methodologies/guidelines have been determined for the assessment and management of surface water bodies and downstream resources (e.g., *Riparian Guidebook, Gully Assessment Procedure Guidebook*). It is recommended that, even though water flow in karst terrain is principally subsurface and not visible, it still requires careful assessment and management.

The objectives of Phase 3 dye tracing investigations are to regionally delineate, for a particular karst unit with significant surface hydrological features and likely subsurface groundwater flows, the following:

- likely recharge areas,
- likely discharge sites,
- principal groundwater flow paths,
- likely location and connectivity of subsurface conduits, and
- likely subsurface flow response times.

Phase 3 investigations are not intended to be all encompassing, but will provide a general idea of sites that may, or may not, require further dye tracing or investigation during operational-level inventories. At the operational level, dye tracing can be focused towards assessing groundwater-related impacts to particular downstream resources or values. Where possible, regional dye tracing should be done well in advance of operational inventories or vulnerability assessments, to allow for careful planning and integration of information.

Suggestion 9. Regional dye tracing should be carried out for a karst unit with significant surface hydrological features and likely subsurface groundwater flows to identify the likely recharge and discharge areas, determine the principal groundwater flow paths, and assess the location and connectivity of subsurface conduits.

4.4.1 Office work and project initiation

Following completion of Phases 1 and 2, the boundaries of the main karst-bearing units will have been delineated for an area, the principal geomorphic and hydrological features identified, and the distribution and intensity of karst development generally understood. This would preferably be compiled in the form of GIS data with various layers of information (see below).

A conceptual design for dye tracing projects should be completed prior to field work. This design should take into consideration the findings of Phases 1 and 2. It will ensure that the overall project objectives are clarified, and will determine favourable locations for dye injections and sampler sites, and frequency of sampling. Appropriate dyes and samplers should be chosen for the site conditions. Various interested agencies (e.g., Federal Department of Fisheries and Oceans and BC Environment) should be informed of the location and time of the dye tracing.

4.4.2 Field work

Background water samples should be taken at injection and collection sites for analysis, particularly if previous dye tracing has been done in the area. Water at the injection and collection sites should be tested for temperature, pH, dissolved oxygen, and conductivity. (Conductivity can sometimes prove an important measurement for assessing the possible sources of water flow, because karst waters generally have a higher conductivity). Water flow estimates should be made at injection and sampler sites. Precipitation data should be obtained from a nearby registered rain gauge, if available. If not available, a simple rain gauge should be set up at a suitable location for the duration of the field work.

Retrieval and replacement of dye samplers should be carried out strictly according to an approved procedure. A labelling protocol and chain of custody should be implemented, with all samples being shipped directly to an approved laboratory for analysis. These samples should be prepared and analyzed according to accepted laboratory standards and procedures. Analytical results should be certified by the laboratory. Following completion of the field testing and analysis, a map (or layer in a GIS data base) should be completed, showing dye paths and travel times of groundwater flow, boundaries of the recharge areas, insurgences, and exsurgences.

4.5 Suggested Standards for Map Presentation, Reports, and Workers

For Phase 1 maps and cross-sections, presentation should be carried out to standards outlined in Part 3 of the SGBM-BC (pp. 13–23). Bedrock mapping symbols should be as indicated in the SGBM-BC, and karst features/hydrological symbols should conform to a chosen standard. For Phase 2, map presentation should be carried out to the general standards of Sections 8 and 9 in the GSTM-BC. It is recommended that mapping for all phases be integrated into a layered GIS system. This information could then be rapidly incorporated into a planning-level karst vulnerability assessment if required (see Section 6.0). Separate layers for the following are suggested: topography, creeks/lakes, boundaries and types of karst units, structural bedrock information, surface karst features, terrain mapping polygons with karst attributes, hydrological data, and subsurface flows/dye trace paths.

One report covering all phases would be acceptable if all phases were completed during a short time frame by one worker. Separate reports are suggested for each phase if they are done sequentially over a period of time or completed by different workers. The reports should cover project objectives, materials used, regional geologic/geomorphologic/hydrologic setting, office and field methodologies, discussion of results, conclusions, and recommendations. Section 11 of the GSTM-BC covers the general scope required for these types of reports. The report should also contain information with respect to data reliability, TSIL, and any limitations (areas not assessed, difficulties in dye tracing, etc.)

A variety of skills, both at professional and technical levels, will be required to carry out a planning-level inventory. It is suggested that Phase 1 be carried out by a professional experienced in bedrock/surficial mapping and karst geomorphological and hydrological processes. A suitably trained technician or professional-in-training could, under the

direct supervision of a qualified professional, be employed to carry out some of the field work.

Phase 2 should be carried out by a professional experienced in terrain mapping and karst processes. It is suggested that a suitably experienced technician could be employed "in tandem" with the professional to mark and locate/measure surface karst features, and rove off the main traverse route to examine any areas of significant interest. In some cases, rapid examination and inspection of cave entrances could be made during the course of the field work. Careful radio communication between the two workers would be essential for this team to be successful.

Phase 3 requires the input of an experienced karst hydrologist during the dye tracing design and data analysis.

4.6 Management Implications

The planning-level karst inventory, as outlined by the three phases above, should be able to provide a data base and framework from which management decisions can be made during forestry activities. Data from the planning level inventory should be in such a format that they could be readily incorporated into an accepted karst vulnerability procedure (see Section 6.0) or, if required, transferred into a forest development plan. **Note:** Phase 3 dye tracing can be a useful management tool for indicating the hydrological sensitivity of both karst and non-karst catchments.

From the planning-level karst inventory, the design of cutblocks and roads for a particular watershed should be able to take into consideration potentially sensitive karst areas. These areas can be either avoided or planned for, thus avoiding possible surprises at the initiation of harvesting or road construction. The implications and costs of various harvesting systems and special road construction methods can also be considered ahead of time.

A similar planning-level karst inventory procedure could be carried out for watersheds undergoing restoration or road deactivation, because potentially well-intentioned work could cause undesirable impacts (e.g., redirection of surface flows into a critical insurgence point). Silvicultural work would also benefit from a better knowledge of the karst unit (e.g., thinning on sensitive sites or using fertilizers/pesticides in sensitive recharge areas).

Costs for the planning-level karst inventory are difficult to determine at this stage because this methodology has not been tried in the field. Costs for terrain mapping at TSIL C are typically $2–5/ha, but are highly dependent on project objectives, access, and map format requirements. If the intention is to use Phase 2 data for a vulnerability assessment, these costs could increase slightly because more detailed field checking might be required. The costs for Phase 1 are anticipated to be less than those for Phase 2, but depend on access and project requirements (e.g., helicopter time for some sites will significantly increase costs). Materials and analyses for dye tracing are relatively inexpensive (e.g., $120/dye injection and $45/sample analysis) considering the important information that can be obtained for both inventory and management purposes. Most of the costs of the dye tracing work are in the labour required for design, implementation, and reporting of results.

5.0 PROPOSED OPERATIONAL-LEVEL KISP (1:10 000 to 1:5000 MAP SCALES)

5.1 Objectives and Approach

This section outlines a proposed methodology for the operational-level karst inventory at 1:10 000 to 1:5000 map scales (see Figure 6). While this level of karst inventory can include both surface and subsurface inspection and evaluation, this section focuses on the surface. The inspection of caves is a detailed inventory in its own right and is beyond the scope of this document.

The principal objectives of the operational level karst inventory are:

- to identify resource values and features for management according to FPC requirements,
- to identify and classify surface and subsurface karst features,
- to identify the need for further specialized inventories (e.g., palaeontological, subsurface biota),
- to refine the three-dimensional nature of a specific part of a karst unit, and
- to determine the need for further detailed dye tracing, due to subsurface hydrology concerns or downstream resource impacts.

One underlying aim of the operational level karst inventory is to provide site-specific information for forest development (e.g., proposed cutblocks or roads). This level of inventory should both reinforce and expand upon the work conducted during the reconnaissance- and planning-level karst inventories.

Operational karst inventories are intended to build upon the recreation inventories normally carried out by forest districts or forest licensees. In most instances, the operational karst inventory would be initiated in support of an application for forest development at the cutblock level. Site-specific impact assessment would rely on the inventory data collected at this "fine filter" level.

The operational karst inventory would typically focus on a small area of karst that probably occurs within a larger karst system or unit. The size of the host system in relation to the karst area of interest would need to be considered before setting inventory boundaries. An important unit at this level would be the karst catchment or recharge area, which might extend beyond topographic divides. This recharge area could include both the karst hydrological system and an upland, non-karst catchment area. The regional recharge area should be delineated by regional dye tracing at Phase 3 of the planning-level inventory (see Section 4.4).

To effectively consider the karst ecosystem for management purposes, the inventory area must be "projected" underground and will require some level of subsurface inspection. This will assist in the evaluation of the three-dimensional aspects of the karst ecosystem. It is critical at this stage to recognize the linkages that exist between the surface and subsurface attributes of the karst system. The principal surface attributes that should be recorded during the operational-level inventory include all those required at Phase 1 and Phase 2 of the planning-level inventory, plus some others, as indicated with three asterisks in Table 9.

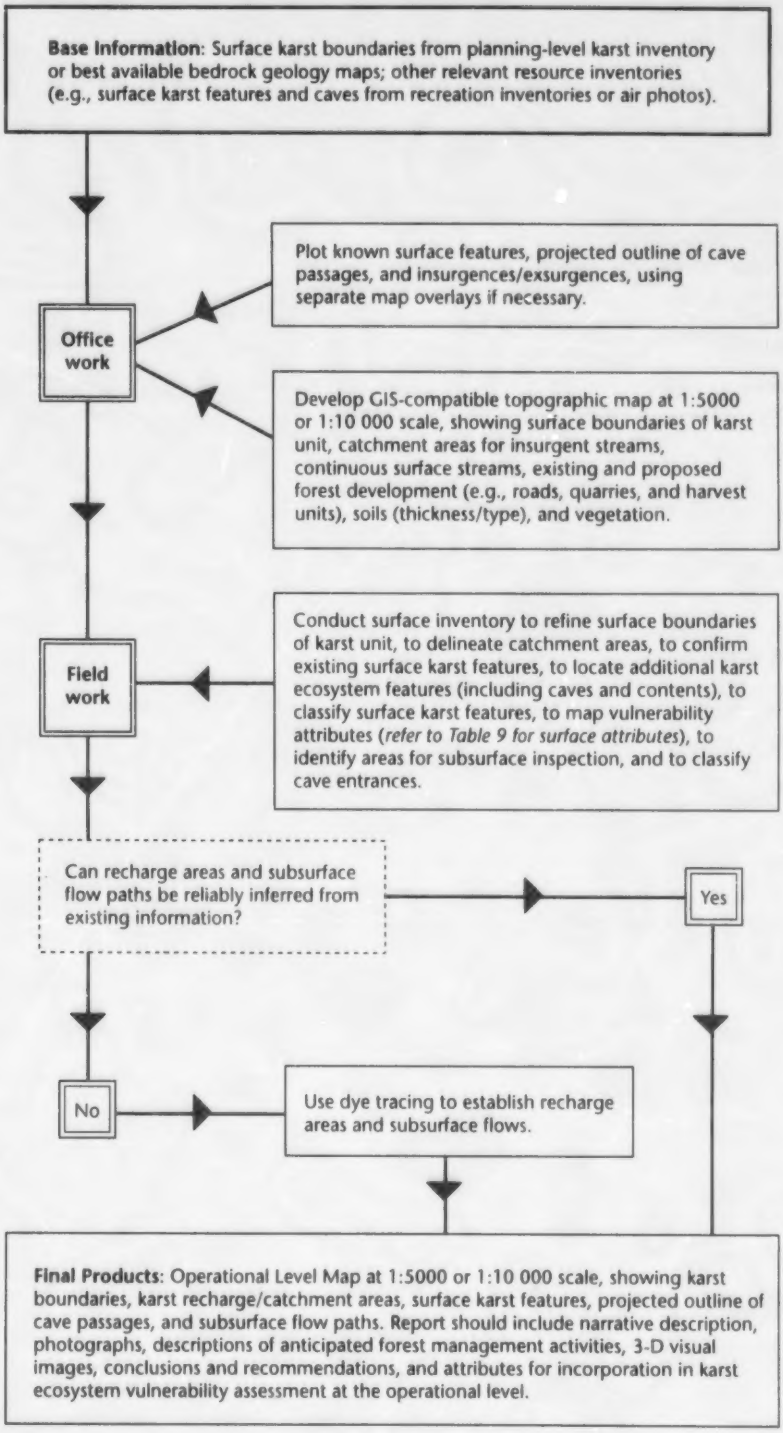

Base Information: Surface karst boundaries from planning-level karst inventory or best available bedrock geology maps; other relevant resource inventories (e.g., surface karst features and caves from recreation inventories or air photos).
Office work
Plot known surface features, projected outline of cave passages, and insurgences/exsurgences, using separate map overlays if necessary.
Develop GIS-compatible topographic map at 1:5000 or 1:10 000 scale, showing surface boundaries of karst unit, catchment areas for insurgent streams, continuous surface streams, existing and proposed forest development (e.g., roads, quarries, and harvest units), soils (thickness/type), and vegetation.
Field work
Conduct surface inventory to refine surface boundaries of karst unit, to delineate catchment areas, to confirm existing surface karst features, to locate additional karst ecosystem features (including caves and contents), to classify surface karst features, to map vulnerability attributes (refer to Table 9 for surface attributes), to identify areas for subsurface inspection, and to classify cave entrances.
Can recharge areas and subsurface flow paths be reliably inferred from existing information?
Yes
No
Use dye tracing to establish recharge areas and subsurface flows.
Final Products: Operational Level Map at 1:5000 or 1:10 000 scale, showing karst boundaries, karst recharge/catchment areas, surface karst features, projected outline of cave passages, and subsurface flow paths. Report should include narrative description, photographs, descriptions of anticipated forest management activities, 3-D visual images, conclusions and recommendations, and attributes for incorporation in karst ecosystem vulnerability assessment at the operational level.

FIGURE 6 *Proposed operational-level KISP methodology.*

In some cases, there may be a need to assemble a multi-disciplinary team for very detailed inventories of significant karst ecosystems that might encompass multiple resources and values. Specialists may include geomorphologists, hydrogeologists, biologists, palaeontologists, archeologists, etc., as required by the site conditions. Knowledgeable and experienced speleologists will normally be required for the safe and efficient investigation of technically difficult and/or sensitive caves.

5.2 Methodology

The operational-level karst inventory should focus on identifying karst elements (e.g., surface karst features, soil thickness) that are relatively stable and reliably mapped. The quantity and/or quality of other, less fixed, biophysical attributes (vegetation, wildlife, etc.) should also be inventoried if the information is required for the assessment and management of a particular karst area.

In most cases, the operational karst inventory will include a combination of desktop review, field work (ground searching and subsurface inspection), data analysis, classification of surface and subsurface karst features, map preparation, and report compilation.

5.2.1 Office work phase

The office work phase of an operational-level karst inventory should involve the following tasks:

1) Reviewing the available data from reconnaissance- and planning-level karst inventories, including any dye tracing results. Obtaining any other karst inventory or cave information for both the area of interest and adjacent areas.
2) Obtaining basic information on the karst area from available air photos, and from topography, bedrock geology, and surficial geology/terrain maps.
3) Determining any relevant requirements or protocols from FPC guidelines and higher-level plans, including cave/karst management plans. Reviewing types of proposed forest activity (e.g., location of roads, harvesting methods). Obtaining any local knowledge on the area or adjacent areas (e.g., windthrow).
4) Identifying and gathering any other existing information about the karst unit's landform features, soils, topography, ecosystems, flora, and fauna using available mapping and other inventories (e.g., terrestrial ecosystem, terrain mapping, fish habitat, forest cover; see Section 7.0). (This information will assist in later land management decisions that consider possible issues related to endangered animal and plant species, biodiversity, downstream fisheries, domestic and/or livestock water supply, recreation, etc.)
5) Constructing a base topographic map at the required scale, preferably in digital format using a GIS system with a series of layers. Developing layers for bedrock geology (e.g., karst boundaries), creeks, proposed forest activity (e.g., roads/cutblocks), soils (thickness/type), and vegetation. Plotting any known surface karst features on the base map using points and approved symbol conventions. Plotting any known cave passage outlines in plan view. Plotting any known insurgences or exsurgences (e.g., swallets or springs, respectively).

6) Developing a plan for field work (e.g., task list), including appropriate methods for ground searches and subsurface inspections.

5.2.2 Field work phase

In order to complete an operational karst inventory of an area, detailed ground searching and mapping are required to both record and measure surface attributes (e.g., soil thickness, epikarst distribution, and openness). For karst inventories in forested areas, it is not practical or economically feasible to search 100% of the area. Therefore, an appropriate method of inventory sampling is required. Surface mapping is a critical part of the inventory methodology for delineating boundaries of areas or zones of equivalent attributes (e.g., soil thickness, groups of sinkholes).

The time and costs required to complete more intensive surveys are important considerations. Larger and more complex units may require many repeat visits and take several years to complete, particularly for subsurface inspection/exploration. This may also be compounded by other problems of poor access and unfavourable weather (e.g., heavy rainfall/floods hindering subsurface work).

A variety of methods for surface inventory sampling techniques can be used for both searching and mapping of attributes, including:

- reconnaissance surveys,
- judgemental surveys,
- multiple transect or grid surveys, and
- total grid surveys.

These methods can be combined, stratified, or modified to suit field conditions. Details on how each of these methods are currently used in British Columbia are included in Section 2.2. It is suggested that these methods be slightly modified and adapted to incorporate mapping of attributes as well as the location and identification of karst surface features. The surface inventory method chosen should sample the core karst attributes identified in the desktop analysis, locate further significant karst features (e.g., insurgences and discharge points), and map required attributes (e.g., soil thickness, epikarst extent, and openness).

The reconnaissance (or walkabout) sampling survey could be used as the first field phase in combination with later more detailed judgemental or grid surveys. The reconnaissance survey consists of a transverse line across the inventory area or a search along proposed road locations.

The judgemental survey is based on the recognition that karst development does not occur in a random fashion, and that it is possible to identify associations between karst development and terrain variables (e.g., the correlation between swallets and upper limestone contacts or the inverse correlation between steep hill slopes and dolines). By using this approach, an experienced field worker can predict where features are more likely to be found, and the traverse routes can be designed and optimized accordingly. This can be an effective method for concentrating field work on critical areas and avoiding detailed work in areas of less concern.

The multiple transect or grid survey is useful where cave/karst features (i.e., possible cave entrances) are spread more diffusely or randomly

throughout an area, rather than being concentrated at predictable locations. The grid layout, spacing, and orientation of search lines should be based on both practical considerations (e.g., understorey thickness, terrain steepness) and an assessment of where the most information might be obtained. Typically, these grids can be constructed by a single compass person along a centre line, with rovers identifying/locating/mapping surface karst features and relevant attribute information.

The total grid method could be employed for critical areas within cutblocks. This method requires surveying a regular grid system of an appropriate size (e.g., 20 by 20 m for intensive searches). Surface karst features and other attributes are located and mapped onto a series of set point locations.

The following outlines the steps that should be considered in completing operational karst inventory field work:

1) Select an appropriate surface inventory sampling technique.
2) Locate any significant surface karst features using GPS or a compass bearing and distance to a fixed marker (e.g., survey line/falling corner). Mark in the field as required. Provide narrative descriptions, measurements, photos, etc. for all features or zones.
3) Identify, locate, and map required attributes where identified in Table 9 (e.g., epikarst zones, exposed bedrock, natural windthrow, surface overflow channels).
4) Systematically measure and record the approximate depth of soil by test pits or probing. Take measurements both on ridges and in depressions. Estimate the depth of openness in the epikarst.
5) Measure and record the electrical conductivity of water at insurgences and exsurgences with a portable meter. (This information is useful for assessing the source and nature of subsurface flows, since the higher the conductivity, the more the water has been in contact with karst.) Estimate flow rates and describe weather conditions for the previous 24 hours, if known.
6) Classify significant surface karst features (see Section 5.2.3 below).
7) Inspect cave entrances and classify as required (see Section 5.2.3 below).
8) Review the results of the initial survey to determine where more intensive ground coverage may be required.
9) Conduct detailed dye tracing, if required (see Section 7.1). **Note: At the operational level, it may be necessary to carry out dye tracing under various discharge conditions.**

5.2.3 Classification of karst geomorphic features, biota, and habitats

Several classification systems for karst geomorphic features have been advanced. Classification of karst features can be by their position, function in a hydrological regime, or genesis (Ford and Williams 1989). The placement of a given karst feature within a classification system assists in its hydrological and geomorphological interpretation.

A surface karst feature classification system has been developed by one of the authors, and is presented in Appendix 2. This classification system can be used to determine the relative significance of karst features to assist with subsequent management decisions.

The classification of subsurface karst or cave features has been addressed by the Cave/Karst Management Handbook for the Vancouver Forest Region (1994). This classification system is based on a method from New Mexico. Karst habitats or karst "biospaces" may be classified in terms of their quality or importance. They can be mapped as part of an operational level inventory to assist in karst management decisions.

5.2.4 Suggested standards for reports and data presentation

The data collected from operational karst inventories should be organized and presented spatially on a map, using a GIS system, if possible. The methods and standards for mapping should conform with those endorsed by the Resources Inventory Committee (RIC), where available (e.g., GSTM-BC). Where no RIC standards exist, methods and standards that have been previously approved by a recognized organization with jurisdiction could be used, where appropriate (e.g., UIS cave symbols). Map data should be produced in a format consistent with GIS systems used by forest districts, regions, and licensees.

The base map/data developed during the office work phase should be used to incorporate the following data into separate layers/overlays:

1) Plot new surface karst features on the base map using points and approved symbol conventions.
2) Plot new cave passage outlines in plan view.
3) Plot new surface hydrological features such as insurgence and exsurgence sites (i.e., swallets or springs), dry valleys, and overflow channels.
4) Map the distribution and depth of exposed epikarst and soil types.
5) Delineate the recharge area for both the karst system as a whole and insurgence sites, using appropriate line work to indicate known, probable, and possible limits.

The map layers developed from the operational level inventory can then be used for a vulnerability assessment (see Section 6.0).

The report completed for the operational-level inventory should cover the objectives of the inventory, the methodology, and the results, and provide conclusions and recommendations to assist operational staff, both from government agencies and forest companies, in making management decisions. They should be written in technically accurate language that is understandable to a range of possible readers from management to field operators. Rationale should be provided to support the writers' conclusions and recommendations for any suggested management prescriptions.

The report should include the following essential or critical items:

1) Inventory objectives, scope, limitations, and location.
2) Who completed the work, for whom, and when. Length of time in the field. Weather conditions. Areas examined and areas not examined, with explanations.
3) List of information used (e.g., maps, airphotos, previous karst data, guidelines).
4) Description of anticipated forestry activities (e.g., harvesting methods, road construction techniques).

5) Background description of the regional geological, geomorphological, hydrological, and biophysical setting, with particular reference to adjacent areas.
6) Description of field methodologies, classification systems, and equipment used.
7) Detailed description of karst within and adjacent to the area of interest, including comments on the distribution, types, and openness of surface and subsurface karst features, the surface and subsurface hydrology, slope, and soil conditions. Results can be in the form of narratives, tables, or figures.
8) Discussion of the potential effects of forest harvesting/road construction within the karst area of concern, including comments on the possible consequences of these activities.
9) Conclusions and recommendations for management prescriptions or mitigative measures (e.g., buffers along edges of sinking streams).

Attachments or appendices should include:

1) Regional location map (1:20 000 scale or greater).
2) Detailed 1:5000 or 1:10 000 scale map with topography, surface hydrology, karst feature distribution, likely subsurface hydrological connections, epikarst openness, and soil thickness.
3) Three-dimensional schematics or computer drawings of the karst system in perspective view (emphasizing the types/extent of surface/subsurface linkages).
4) References and glossary.
5) Photographs.

5.3 Management Implications

Operational karst inventories should provide a level of detail appropriate to the particular type of forest development proposed. Site-specific karst inventories should help decision making and ensure compliance with the Interim Karst Management Guidelines (under development). Operational-level karst inventories should also provide sufficient information for impact assessments, with respect to other resources or values (e.g., downstream fisheries).

Costs for completing operational-level karst inventories will vary greatly and are difficult to generalize. They are highly dependent upon: terrain/karst conditions (e.g., number of surface features), percentage of coverage required for an area, ground search method employed, vegetation cover (density of understorey), season, ease of access to the work area (e.g., helicopters for remote locations), and amount of subsurface inspection done or required. A base figure of $50/ha could be considered a "ballpark" estimate for a typical operational-level karst inventory on a coastal cutblock. This cost would cover the crew travel/field expenses, the location and identification of surface karst features, the examination of cave entrances, and the completion of a report/map. Costs could increase significantly if large numbers of surface features are found or if extensive subsurface inspection is required.

It is suggested that procedures be developed to ensure that sensitive karst inventory data (e.g., cave entrance locations) are kept secure. A

secure/coded layer could be developed within a GIS system for cave locations to allow access to only specified personnel.

In general, the personnel who complete the operational karst inventory work should have an appropriate combination of education and experience, and be well-versed in karst and forestry processes and issues. They should be familiar with surveying and mapping procedures, and with the completion of technical reports and maps. Experienced speleologists will be required for subsurface investigations, particularly in technically difficult and/or sensitive caves.

At this stage, it is difficult to determine the specific role of, or the need for, professional involvement (e.g., RPF, P.Geo., RPBio., P.Ag., P.Eng.), but due diligence, liability issues related to the FPC, and the more detailed technical nature of the operational level inventory may make their participation an eventual requirement. The number of professionals in British Columbia with experience in karst and forestry issues is probably limited at this time. Further discussion of this particular issue is anticipated.

6.0 KARST VULNERABILITY METHODOLOGIES AND POSSIBLE APPLICATIONS FOR FORESTED KARST AREAS OF BRITISH COLUMBIA

6.1 Introduction and Background

Karst vulnerability methodologies have been extensively used for the evaluation of karst hydrological systems, particularly with respect to the pollution of karst aquifers and groundwater (Aley and Aley 1993; European Commission Report 1995). Two examples of groundwater vulnerability methodologies are summarized below.

The EPIK system for karst groundwater protection in Switzerland (Doerfliger 1996) was specifically designed to evaluate the vulnerability of karst spring catchments to natural and anthropogenic impacts. This method requires the mapping of four attributes:

- Epikarst (E). Identifying surface karst features (e.g., cave entrances, sinkholes, fractured outcrops, dry valleys).
- Protective cover (P). Categorizing soil conditions (e.g., soil type, depth, permeability).
- Infiltration conditions (I). Locating stream beds and banks, perennial and intermittent swallets, perennial and intermittent streams feeding a swallet or sinkhole, and infiltrating streams.
- Karst network development (K). Characterizing the development of the karst network (e.g., well or poorly developed).

Each of the four attributes is given a weighted numerical rating, and a spatial distribution map is created for each of the attributes using a GIS system. An algorithm for E, P, I, and K is then used to develop a vulnerability map for the catchment, identifying areas of high vulnerability (S_1), moderate vulnerability (S_2), and low vulnerability (S_3).

Another approach for assessing karst groundwater vulnerability is hazard area mapping of recharge areas (Aley and Aley 1993). The aims of this method are to identify and characterize the recharge areas that may pose varying water quality hazards to significant cave areas. The principal

technique used for this methodology is groundwater tracing using fluorescent dyes. After a thorough reconnaissance of a particular area, sites are identified where water sinks (e.g., swallets) and where it emerges (e.g., springs). Dyes are injected at the sinks and cumulative charcoal samplers are set at emergent sites. The specific recharge area for each spring can then be identified and rated, depending on downstream impacts, using four groundwater contamination hazard categories (low, moderate, high, and very high).

Karst vulnerability assessment has also been adapted for forest management purposes in temperate forested karst areas in Southeast Alaska (e.g., Aley et al. 1993; Harza 1995; Baichtal and Swanston 1996; Baichtal 1997; USDA Forest Service 1997) and Tasmania (e.g., Eberhard 1996). Examples of these methodologies are summarized below.

In southeast Alaska, a methodology used by the U.S. Forest Service, as part of the Tongass Land and Resource Management Plan (TLMP), focuses on the potential impact of forestry on karst systems (USDA Forest Service 1997). The Alaskan system is a four-step process that i) identifies potential karst lands on a regional basis, ii) conducts inventories of karst resources, iii) delineates karst hydrologic systems and catchment areas, and iv) assesses the vulnerability of karst terrain to forest management activities. Eight classification criteria are used to delineate the karst system and contributing catchments into low, moderate, and high vulnerability. Some of these criteria include epikarst depth, presence of surface karst features, soil type and depth, presence of caves, slope gradient, and connectivity to fish-bearing streams and/or domestic watersheds (see Table 12). The methodology employs a simple default system, whereby if one of the criteria listed under the high vulnerability category occurs in an area, then that area is classified as high vulnerability for forest management purposes.

The default system is largely driven by the *U.S. Federal Cave Resources Protection Act* of 1988. The Act requires the protection of caves found to be significant under the definitions of the Act. U.S. Forest Service Regulations further define what constitutes a significant cave. The standards and guidelines for karst and cave resources under the TLMP are intended to maintain the function and biological significance of karst systems, while allowing for other uses of the land. The management approach focuses on protecting the hydrologic and atmospheric connections of karst systems. Southeast Alaska's process for assessing karst vulnerability is presently under review to clarify the intent and direction of the recommended procedures (J. Baichtal, pers. comm., 1999).

In Tasmania, a zoning scheme differentiating areas into high, medium, and low sensitivity with respect to karst values has been developed for forested areas (Eberhard 1996). The principal concepts and sensitivity concerns incorporated into the zoning scheme include:

- the effects of human disturbance on karst environments and biological communities,
- the maintenance of natural karst processes, as well as individual landforms and their contents,
- the hydrological and meteorological pathways connecting karst systems,
- the karst catchments (as well as the non-karst catchments) of a system,

TABLE 12 *Vulnerability classification criteria used in southeast Alaska (taken from USDA Forest Service 1997)*

Low vulnerability karst lands

Classification Criteria. Low vulnerability karst lands are those areas where resource damage threats associated with land management activities in the areas are not likely to be appreciably greater than those posed by similar activities on non-carbonate substrate. Some characteristics of these lands are:

(a) Karst development is limited or has been modified by glaciation.

(b) Epikarst development is relatively shallow.

(c) Solutional karst features are present but not numerous.

(d) Soils are primarily mineral, soil depth is shallow to deep, soils are moderately well to well drained, parent material is the carbonate substrate, glacial till, or volcanic.

(e) No caves are present.

(f) There are no slopes > 72%.

(g) The karst hydrologic system does not contribute waters to Class I or Class II streams and/or domestic watersheds.

(h) They lie within a watershed that contributes surface waters to a karst area determined to have a low vulnerability.

Moderate vulnerability karst lands

Classification Criteria. Moderate vulnerability karst lands are those areas where resource damage threats associated with land management activities in the areas are appreciably greater than those posed by similar activities on low vulnerability karst lands. Some characteristics of these lands are:

(a) Karst systems are moderately well developed.

(b) Epikarst is up to 8 feet in depth.

(c) Solutional karst features are present but not numerous.

(d) Soils are a mosaic of both mineral and organic. Mineral soils vary from shallow to deep, and are well drained, and parent material is the carbonate substrate. Organic soils are shallow and well drained. If the soil was displaced from the bedrock, it would be retained in the adjacent solutional channels of the epikarst. The percentage of bare rock would increase but the soils would not be transported beyond the rooting depth of young conifers.

(e) No caves are present.

(f) There are no slopes > 72%.

(g) The karst hydrologic system does not contribute waters to Class I or Class II streams and/or domestic watersheds.

(h) They lie within a watershed that contributes surface waters to a karst area determined to have a low vulnerability.

High vulnerability karst lands

Classification Criteria. High vulnerability karst lands are those areas where resource damage threats associated with land management activities in the areas are appreciably greater than those posed by similar activities on low or moderate vulnerability karst lands. These are the areas contributing to or overlying significant caves and areas containing a high density of karst features. Some characteristics of these lands are:

(a) Karst systems are extremely well developed.

(b) Epikarst is greater than 8 feet in depth and may be open to the lateral karst conduits at depth.

(c) Solutional karst features are numerous.

(d) Soils are primarily shallow, well-drained organics. Exposed bedrock areas are common to extensive. If the soil is displaced from the bedrock, it may be retained in the adjacent solutional channels of the epikarst; however, the percentage of bare rock would greatly increase and the soils most likely would be transported beyond the rooting depth of young conifers. If the karst systems are extremely well developed and open, soils may not be retained within the epikarst channels. They would be rapidly transported to the lateral karst conduits at depth.

(e) Caves may be present.

(f) Karst areas may contain slopes > 72%.

(g) The karst hydrologic system may contribute waters to Class I or Class II streams and/or domestic watersheds.

(h) They lie within a watershed that contributes surface waters to a karst area determined to have a high vulnerability.

- the incomplete exploration of karst environments and the potential to enhance knowledge of cave development and hydrology, and
- the notion that the significance of karst areas is likely to change with time as more knowledge is obtained.

The Tasmanian sensitivity method used various criteria to define the different types of sensitivity. For example, low sensitivity karst zones include those areas outside the catchments of significant and sensitive karst systems. Medium sensitivity zones are areas where karst values are known or likely to be present in a catchment, and where the significance of those values is such that land-use activities could affect them. High sensitivity zones are areas that contain highly significant karst values, or where it is extremely probable that these values would eventually be found. These high sensitivity zones might include areas:

- underlain by significant caves,
- with a high density of karst features (e.g., sinkholes, stream sinks, caves),
- that suggest the presence of underlying caves (e.g., by a high density of stream sinks, cave entrances, and sinkholes),
- that are catchments to significant cave areas, and
- where lithological or structural geological considerations suggest the presence of underlying caves.

From the above and other literature, it is apparent that the term "karst vulnerability" is not well defined, and has been used by a variety of workers for different purposes. It is therefore suggested (based on ideas from the European Commission Report 1995) that, in order to provide clarity in vulnerability mapping, it is critical:

- to define the term "vulnerability" and the other terms used,
- to indicate the overall objectives of the vulnerability methodology,
- to describe the basis for the various vulnerability categories, and
- to ensure that the scale of mapping used can meet the objectives.

It is also suggested that the British Columbia karst vulnerability methodology focus on the "intrinsic" (or internal) factors of karst ecosystems, which can be defined as "the natural factors associated with, and inseparable from, the karst ecosystem" (e.g., lithology, hydrology, geomorphology, air, and biota). These intrinsic factors are separate from extrinsic factors that are imposed on a karst ecosystem by natural processes (e.g., windstorms, wildfire) or human-caused events (e.g., forest harvesting, roads).

6.2 Concepts and Definitions for a Proposed Karst Ecosystem Vulnerability Methodology for Forested Areas of British Columbia

In order to provide a comprehensive karst vulnerability mapping tool for British Columbia, all aspects of a karst ecosystem must be taken into consideration. This concept differs from the objectives of the karst vulnerability systems summarized above, in that they have focused on only selected parts of the karst ecosystem. Therefore, the prime objective of the karst vulnerability system for British Columbia must be to evaluate all four fundamental environmental states of the ecosystem: **air, water, land, and biota.**

Suggestion 10. The prime objective of the karst vulnerability system for British Columbia must be to evaluate all four fundamental environmental states of the karst ecosystem: **air, water, land, and biota.** The assessment should focus on the intrinsic or natural factors associated with, and inseparable from, the karst ecosystem.

This approach to karst ecosystem vulnerability mapping must be based on sound principles supported by scientific knowledge. It should be understood that:

- Karst ecosystems are complex, interwoven networks of attributes related to the fundamental environmental states of air, water, land, and biota.
- Karst ecosystems are sensitive to change.
- Karst ecosystems are constantly changing.
- People can be part of karst ecosystems and influence them.
- Karst ecosystems must be viewed at a variety of scales, from the very large (total system) to the very small (microcavity).

Karst ecosystem vulnerability mapping for the purposes of this report can be defined as "a hazard assessment methodology for evaluating the relative ease with which a karst ecosystem might be changed negatively (or harmed) by an imposed external activity."

Karst sensitivity can be considered as "the inherent susceptibility of a particular karst ecosystem attribute (e.g., groundwater) to change."

A karst attribute can be defined as "a feature that is part of a karst ecosystem and is related to one or more of the fundamental environmental states of the ecosystem: air, water, land, or biota."

Forestry and land-use management activities, and other extrinsic (or external) factors, such as the location of downstream fisheries, were excluded from this vulnerability methodology. These external factors could, however, be mapped out separately at a similar scale to the vulnerability mapping so that they could be viewed side-by-side or overlain on the karst vulnerability map. From the two maps, it would then be possible to assess the overall risk of proposed activities within a particular karst area.

Existing karst vulnerability methodologies vary from numerical-based algorithms (e.g., EPIK) to more simple, single-attribute controls (e.g., southeast Alaska system). Both methodologies have advantages and disadvantages. For example, the data for the EPIK system are controlled by a variety of numerically rated attributes that are summed and weighted. While the EPIK system considers a variety of factors, it could also be considered complex when compared to the non-numerical southeast Alaska system. With this in mind, it is suggested that karst ecosystem vulnerability methodology for British Columbia use a combination of these approaches. It should be simple and flexible, but also broad enough in scope to consider as much of the karst ecosystem as possible.

Karst ecosystem vulnerability assessments could possibly be done at both the planning- and operational-level karst inventories. In the former, it is suggested that the broad attributes mapped during Phase 2 of the inventory process (e.g., karst features, slope characteristics and gradient,

soil cover and types) could be categorized or incorporated into a simple vulnerability rating system. This simple system would focus primarily on the land and water environmental states of the karst ecosystem, and could be used as a coarse planning tool for assessing the risk of proposed forest management activities in a karst area. A more rigorous and detailed methodology, that could easily incorporate all four environmental states of the karst ecosystem, could be used at the operational level. The basis of this methodology is detailed in the next section.

Suggestion 11. Karst ecosystem vulnerability assessments could be done during Phase 2 of the planning-level inventory to provide a broad planning tool for assessing the risk of proposed forest management activities in a karst area. A more rigorous and detailed assessment could be carried out at the operational-level inventory, and could incorporate all four environmental states of the karst ecosystem: air, water, land, and biota.

6.3 An Approach for Karst Ecosystem Vulnerability Mapping in Coastal Forested Areas of British Columbia

This section outlines an approach for karst ecosystem vulnerability mapping using data from coastal forested areas of British Columbia. The data and categories developed will probably require some refinement for the interior of British Columbia.

As stated above, karst ecosystems are complex, interwoven networks of attributes related to the fundamental environmental states of air, water, land, and biota. In order to develop a vulnerability methodology to assess this complex ecosystem, it is necessary, firstly, to break the karst ecosystem down into its four fundamental environmental states and, secondly, divide these into broad components or sub-states. These sub-states can then be categorized for vulnerability using a subjective rating system with values of low, moderate, or high. After each of these sub-states has been categorized, it should then be possible to "reconstruct" the whole ecosystem and determine an overall vulnerability rating (see Figure 7). It should be realized at the outset that this type of approach could be considered conceptually flawed because of the tightly interwoven nature of the ecosystem. Whether it is possible to break down an ecosystem and then re-build it is probably open to debate. However, it should be possible to do so, if a relatively broad, rationalized view is taken, and a focus on minute details is avoided.

The various environmental states and sub-states are discussed below and summarized in Tables 13 to 16. These tables provide site examples for low (L), moderate (M), and high (H) vulnerability categories for the various sub-states.

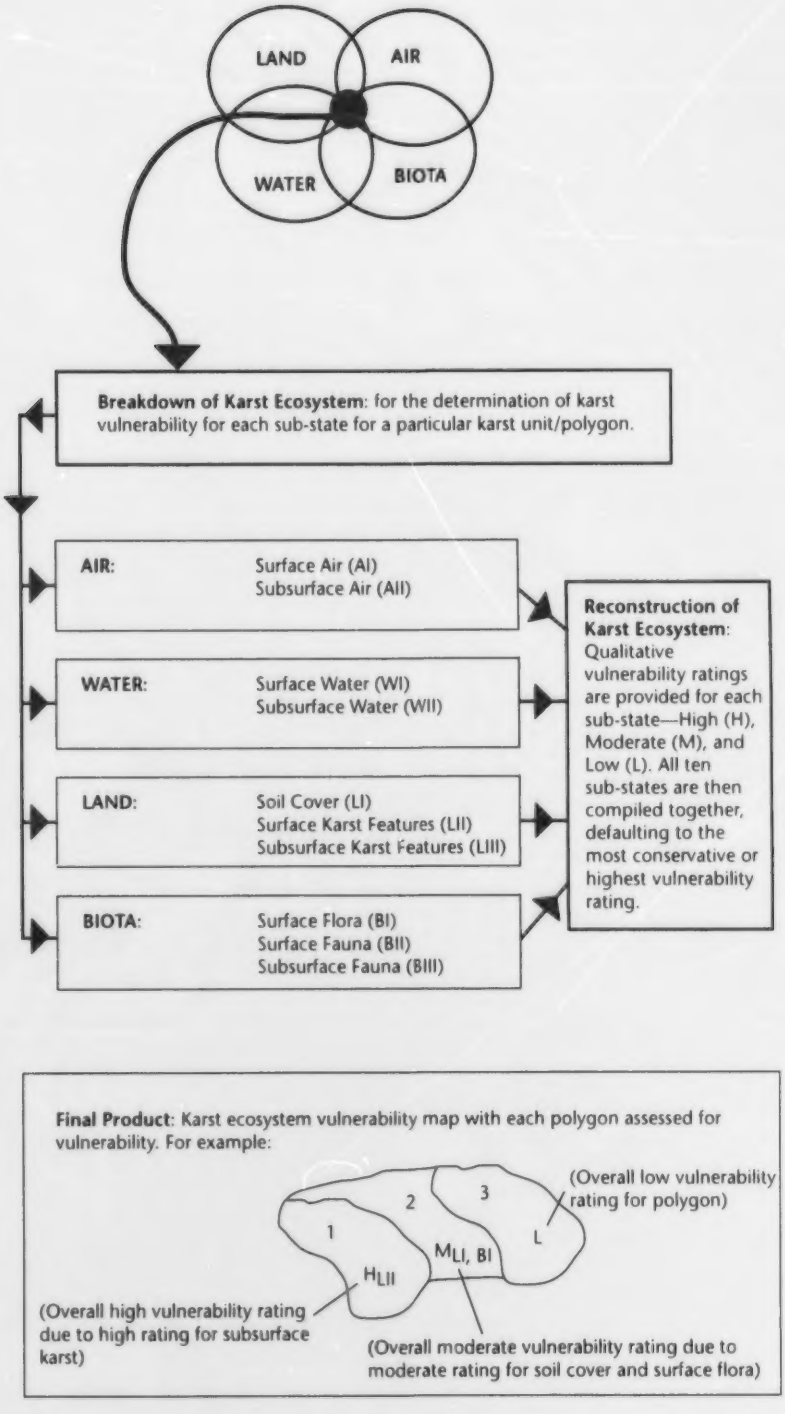

LAND
AIR
WATER
BIOTA
Breakdown of Karst Ecosystem: for the determination of karst vulnerability for each sub-state for a particular karst unit/polygon.
AIR:
Surface Air (AI)
Subsurface Air (AII)
WATER:
Surface Water (WI)
Subsurface Water (WII)
LAND:
Soil Cover (LI)
Surface Karst Features (LII)
Subsurface Karst Features (LIII)
BIOTA:
Surface Flora (BI)
Surface Fauna (BII)
Subsurface Fauna (BIII)
Reconstruction of Karst Ecosystem: Qualitative vulnerability ratings are provided for each sub-state—High (H), Moderate (M), and Low (L). All ten sub-states are then compiled together, defaulting to the most conservative or highest vulnerability rating.
Final Product: Karst ecosystem vulnerability map with each polygon assessed for vulnerability. For example:
1
2
3
L
MLI, BI
HLII
(Overall low vulnerability rating for polygon)
(Overall high vulnerability rating due to high rating for subsurface karst)
(Overall moderate vulnerability rating due to moderate rating for soil cover and surface flora)

FIGURE 7 *Suggested karst ecosystem vulnerability methodology using four environmental states of the karst ecosystem.*

Air (A)

Air is the one fundamental state of the karst ecosystem that is typically given the least attention, but it can play an integral role in the well-being and health of the system. The two principal sub-states are Surface Air and Underground Air (Air I and II, respectively). The exact location where surface air ends and subsurface air begins is difficult to define, but it is assumed to be close to the boundary of light and darkness. The quality and flow rate of surface air around surface karst features (e.g., sinkholes) can be critical to climatic conditions underground, influencing faunal habitats and speleothem growth. Surface air is also critical for certain fauna and flora around the perimeter of karst features.

TABLE 13 *Qualitative vulnerability ratings for air*

Air sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SURFACE AIR (AI)	Air quality	Temperature range, relative humidity range, etc.	High	large, deep depressions (e.g., doline) where temperature inversion is possible
			Moderate	depressions of moderate depth
			Low	no deep, closed depressions
SUBSURFACE AIR (AII)	Air quality, natural rates of transfer	Temperature range, relative humidity range, etc.	High	atmospheric openings with known surface connections
			Moderate	narrow openings with known surface connections
			Low	no atmospheric openings

TABLE 14 *Qualitative vulnerability ratings for water*

Water sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SURFACE WATER (WI)	Maintain quality and quantity	Number and size of surface karst hydrological features, flow rate, pH, temperature, specific conductance, dissolved oxygen, etc.	High	springs, major sinking streams, swallets
			Moderate	"dry" sinkholes, grykes, no flowing water
			Low	soil-covered karst with diffuse infiltration
SUBSURFACE WATER (GROUNDWATER) (WII)	Maintain quality and quantity	Flow rate, pH, temperature, specific conductance, dissolved oxygen, etc.	High	cave streams, standing water, dripwater
			Moderate	intermittently dry and wet caves
			Low	dry cave systems

TABLE 15 *Qualitative vulnerability ratings for land*

Land sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SOIL (LI)	Maintain soil conditions within acceptable ranges	Soil thickness/ type, epikarst depth, slope (macro/micro), permeability, etc.	High	thin organic veneer over well-developed epikarst
			Moderate	moderate soil thickness
			Low	thin blanket or mantle
SURFACE KARST (LII)	Maintain natural rates of dissolution integrity, etc.	Identification/ number of features, feature size	High	extensive areas of deep epikarst, large sinkhole with steep sideslopes
			Moderate	small surface karst features mantled with variable soil cover
			Low	buried (i.e., soil-covered) karst
SUBSURFACE KARST (LIII)	Maintain cave quality, structural integrity, etc.	Cave entrance width/ height, depth of overlying bedrock, etc.	High	well-decorated caves
			Moderate	caves with features/significant between high and low
			Low	caves with no unusual resource contents or values

TABLE 16 *Qualitative vulnerability ratings for biota*

Biota sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SURFACE FLORA (BI)	Maintain natural communities, populations, and habitats	Species diversity/ density, dominant taxa, presence of unique flora	High	significant areas of unique or rare plants occurring on limestone
			Moderate	some areas of unusual plants, but not extensive or endangered
			Low	deep soils, no unique plants
SURFACE FAUNA (BII)	Maintain natural communities, populations, and habitats	Habitat indicators, presence of unique fauna	High	rare mammals using surface karst habitat
			Moderate	some rare usage of minor surface karst habitats
			Low	no known surface karst-dependent fauna
SUBSURFACE FAUNA (BIII)	Maintain natural communities, populations, and habitats	Habitat indicators, presence of troglobites	High	bat hibernaculum or rare, unique fauna site
			Moderate	suitable habitat, but no evidence of fauna
			Low	active, seasonally flooded caves of limited extent

Water (W)

Water is one of the more studied environmental states of the karst ecosystem and could be considered as the fundamental driving force in the karst dissolution process. In this case, two sub-states are considered, Surface Water and Subsurface Water (Water I and II, respectively). Again the boundary between these two states is not well defined. For example, it is possible to have a stream that disappears and reappears along its length. However, the same light and darkness boundary used for dividing surface air from subsurface air is considered reasonable. As with air, the principal concerns are the sensitivity of water to changes in quality and quantity.

Land (L)

For simplicity, the land (or terrestrial) environmental state can be divided into three sub-states: Soil Cover, Surface Karst Features, and Subsurface Karst Features (Land I, II, and III, respectively). Soil Cover can be considered as any unconsolidated materials overlying the karst bedrock, and includes both genetic surficial materials and weathered bedrock fragments. The distinction between Soil Cover and the other two sub-states is obvious. The distinction between Surface and Subsurface Karst Features is a more difficult boundary to define, but the light and darkness boundary is considered a reasonable guide.

Biota (B)

Karst biota can be divided into three sub-states: Surface Flora, Surface Fauna, and Subsurface Fauna (Biota I, II, and III, respectively). For simplicity, all subsurface biota are considered as fauna because no chlorophyllic biota (e.g., plants) are naturally present underground. The principal aim of categorizing biota is to evaluate an area for unique or rare flora or fauna associations.

Following the rating of sub-states, each of the four states (air, water, land and biota) is assigned the highest rating obtained from the respective sub-states. For example, if the sub-states Surface Flora, Surface Fauna, and Subsurface Fauna for a particular site give a rating of low, moderate, and low, respectively, then the overall rating for Biota would be moderate. A subscript could be used after the rating to indicate which sub-state is the controlling factor (in the above case it would be BII). From the ratings of the four states, it should then be possible to obtain an overall vulnerability rating for a particular karst ecosystem unit or site. Again, the most sensitive value assigned one of the four states is used. For example, if the states for Air, Water, Land, and Biota for a particular site had ratings of low, low, low, and moderate, respectively, then the overall vulnerability rating for the site would be moderate. To be more specific, the overall vulnerability rating could be given a suitable subscript to identify what state and sub-state has driven the rating. The above example would provide an overall vulnerability rating of moderate due to biota associated with surface fauna (MBII). If more than one of the sub-states is the controlling factor, then these could be listed in order of air, water, land, and biota.

One way to obtain a very high vulnerability rating for a particular area would be when two (or possibly three) environmental states all indicate a high rating. In addition, the use of a vulnerability assessment system with

annotated subscripts for the various ratings of ecosystem sub-states would allow forest management prescriptions to address particular concerns at a site.

Suggestion 12. It is suggested that the four environmental states of the karst ecosystem (air, water, land, and biota) be divided into ten sub-states for the vulnerability assessment as follows: Surface Air (Air I), Subsurface Air (Air II), Surface Water (Water I), Subsurface Water (Water II), Soil Cover (Land I), Surface Karst (Land II), Subsurface Karst (Land III), Surface Flora (Biota I), Surface Fauna (Biota II), and Subsurface Fauna (Biota III). These sub-states should be individually rated as low, moderate, or high for a particular karst unit. The overall vulnerability rating for the karst unit would then default to the highest sub-state rating.

6.4 Data Presentation, Integration, and Analysis

To date, this approach to karst ecosystem vulnerability assessment has not been applied in practice. It will, therefore, require considerable testing and refinement. It is intended that the assessment be applied as a mapping procedure incorporated into a GIS system with various layers compiled for each of the environmental sub-states. Data for these layers could be obtained from the appropriate levels of karst inventory information. The karst inventory data could also be refined to assist in developing a suitable format for incorporating them into the sub-state layers. The sub-state layers could then be analyzed by the GIS system to produce a map with an overall karst ecosystem vulnerability rating. This type of mapping methodology would be most useful at planning-level inventory scales.

A possible alternative to the GIS system, particularly at proposed cutblock or road-building scales, would be the development of a tabulated form approach. Each of the sub-states could be set out on a field form and the cutblock or area of interest categorized for each of the sub-states. An overall vulnerability rating could then be obtained relatively quickly for simple sites. For example, a cutblock underlain by carbonate bedrock, with no evidence of subsurface openings or rare surface karst biota, and a blanket (i.e., >1 m) of soil cover, could be evaluated and rated rapidly with little need for GIS mapping techniques.

6.5 Limitations, Strengths, and Weaknesses of the Suggested Approach

Issues such as data collection intensity, data limitations, subjectivity of results, and data reliability will need to be examined further. Additional work will be required to ascertain which measurable attributes and features are needed to categorize the sub-states. British Columbia–based karst research, scientific consensus on results, and field trials may eventually support the ideas proposed above.

In terms of strengths, the proposed methodology for karst ecosystem vulnerability is flexible and well suited to the attributes that occur at any or all levels of the karst inventory process. The methodology can be considered holistic in that it attempts to address the complete karst ecosystem, in contrast to other vulnerability assessments that focus on only parts of the ecosystem. The methodology is applicable to long-term

evaluation of the cumulative impacts of different forest management activities (or successive phases of an activity) and for harvesting rotations. It can also be readily updated as new information becomes available (e.g., a new cave area is discovered).

In terms of weakness, the methodology could be considered excessive because of all the data required to complete the vulnerability assessment. However, in many cases, particularly where no subsurface karst features are evident, the data required could be minimal.

7.0 INTEGRATION OF PROPOSED KARST INVENTORY SYSTEM AND SUGGESTIONS FOR FURTHER WORK

Any well-integrated inventory system developed for differing scales of data collection should have closely knit internal linkages. These internal linkages are required so that the methods of data collection, assimilation, and analysis are systematic, progressing from regional, overview scales (e.g., 1:250 000) to more detailed site-specific scales (e.g., 1:5000). These well-defined linkages are also important for consistency during the exchange of data between the various scales of inventory.

The objectives of this final section are:

- to summarize the linkages between the reconnaissance-, planning-, and operational-level karst inventories,
- to summarize how the proposed karst ecosystem vulnerability assessment could be carried out and used within this framework,
- to show how the three inventory levels might be linked, both in terms of data collection and completion, with other inventory procedures, and
- to outline a series of suggestions for further work to both refine and improve the proposed karst inventory and vulnerability assessment methodologies.

7.1 Summary of Internal Linkages within the Proposed Karst Inventory System

The various scales chosen for the three inventory levels are based on standard geographic mapping scales used in Canada (NTS system with 1:250 000 and 1:50 000 maps), and the currently used mapping scales of the British Columbia forest industry and provincial government (1:20 000, 1:10 000 and 1:5000). The change in scale from reconnaissance- to planning-level inventories is significant, with a five-fold increase in detail from 1:250 000 to 1:50 000 scales and a twelve-and-a-half-fold increase from 1:250 000 to 1:20 000 scales. Significant errors in the transfer of line and polygon data could occur in both of these cases. The change in scale from the planning level inventory (1:20 000) to the operational level (1:10 000 or 1:5000) is less (two- and four-fold, respectively). Therefore, less potential error in the transfer of line and polygon data between the planning and the operational levels is anticipated.

The first stages in determining the karst potential for a region, assuming no existing karst information is available, is to complete a reconnaissance-level inventory (see Section 3.0). From the reconnaissance-level karst inventory (at 1:250 000 scale), it should be possible to determine

which particular bedrock units are likely to be the most significant in terms of karst presence (Criterion 1) and intensity of karst development (Criterion 2). The confirmatory criteria for known caves, surface karst features, and inspection level will add confidence to this information.

Figure 8 is a summary flow chart for the proposed karst inventory system, starting at the reconnaissance level, leading on to the planning and operational levels, with final links to the karst vulnerability assessment methodology.

The boundary lines for the 1:250 000 scale karst unit polygons, taken from the digital bedrock maps of British Columbia, will be reasonably accurate down to a scale of 1:100 000. However, if used directly for Phase 1 or Phase 2 at the planning-level inventory (1:50 000 or 1:20 000), significant boundary errors are likely to occur. To reduce these errors, it is suggested that the original, detailed bedrock maps (with variable scales and coverage), which were the basis for the 1:250 000 digital compilation, be sourced and used at the planning level. These original maps will also probably provide additional information on bedrock lithologies and major structures. To assist sourcing of these original maps, it is suggested that their references be included in the legends of the reconnaissance karst inventory maps. An inset map could also be included on the reconnaissance maps to show the coverage, scales, and overlaps of the original maps. The attributes of bedrock lithology and unit width, determined at the 1:250 000 reconnaissance level, could be used as a preliminary guide at the planning level for bedrock lithology conditions and karst unit widths. However, these data are office-based and will likely require verification and field checking at the planning level.

The planning-level inventory uses a phased approach to assist in data gathering and in defining the direction of work (see Section 4.0). Phase 1, at scales of 1:50 000 or 1:20 000, focuses on identifying the types and boundaries of a karst unit, the adjacent bedrock lithologies, major bedrock structures, and major surface karst and hydrological features. This information can be readily used, or incorporated into Phases 2 and 3, as required. The decision on whether Phase 2 is required or not depends on both the size and complexity of the karst areas under investigation. Phase 2 may not be required for small areas of karst with relatively uniform characteristics. Phase 1 for a small area might be able to readily obtain the karst feature and attribute data suitable for easy incorporation into the vulnerability assessment procedure. For larger and more complex areas (e.g., units with varying intensities of surface epikarst and soil thickness), Phase 2 should be carried out to stratify these areas into sub-areas (polygons) using a modified terrain mapping system. Regional dye tracing (Phase 3) should be carried out only following Phases 1 and/or 2.

The requirement for dye tracing depends on whether: i) recharge areas or subsurface flows can be inferred from existing information (be it surface or subsurface observations), ii) significant karst hydrological features are present (e.g., sinking streams or major springs), and iii) significant or complex subsurface flow paths are present. If the recharge areas and subsurface flow paths are apparent, and there are no significant karst hydrological features, there may be no need to conduct dye tracing. On the other hand, dye tracing may be the only way to investigate complex subsurface hydrological networks (see Section 4.4).

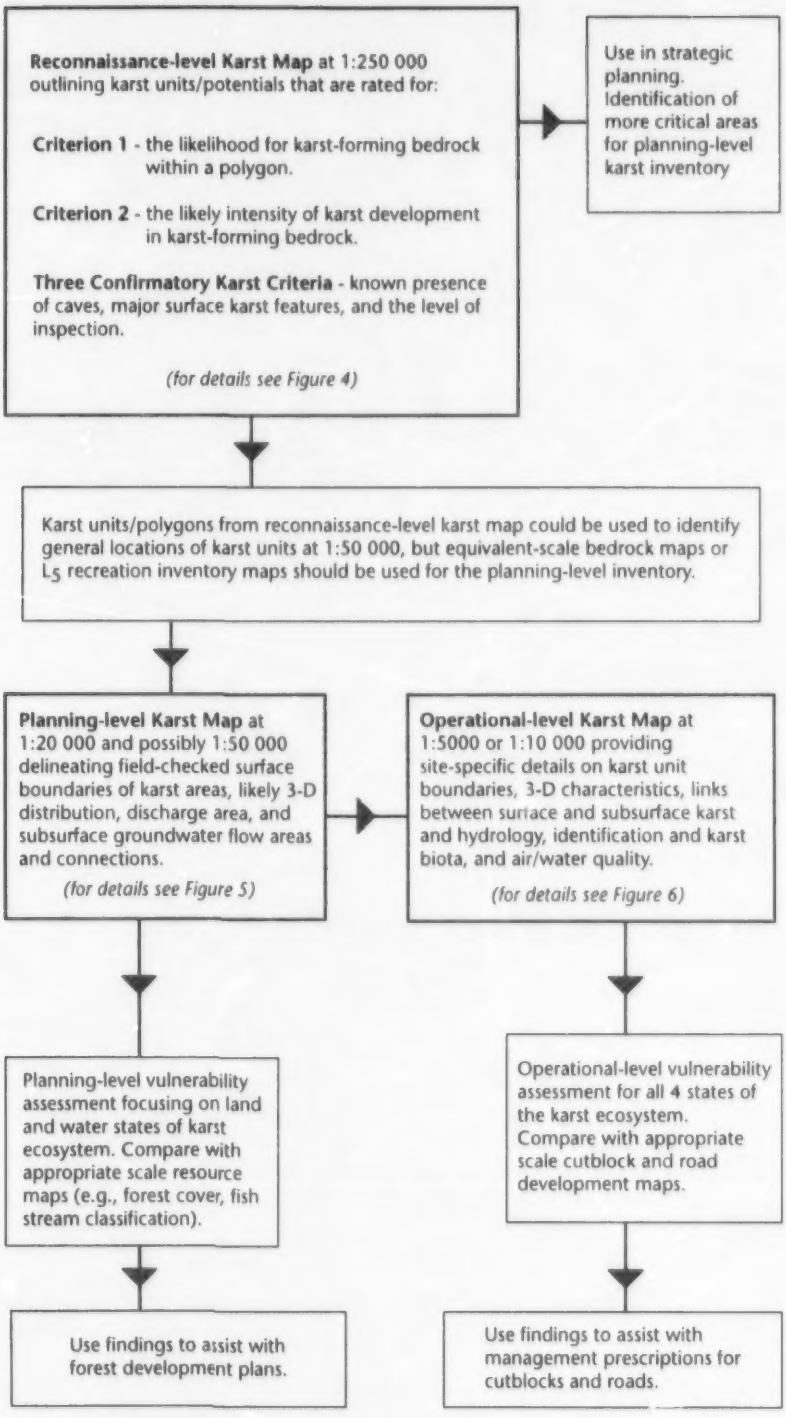

Reconnaissance-level Karst Map at 1:250 000 outlining karst units/potentials that are rated for:
Criterion 1 - the likelihood for karst-forming bedrock within a polygon.
Criterion 2 - the likely intensity of karst development in karst-forming bedrock.
Three Confirmatory Karst Criteria - known presence of caves, major surface karst features, and the level of inspection.
(for details see Figure 4)
Use in strategic planning. Identification of more critical areas for planning-level karst inventory
Karst units/polygons from reconnaissance-level karst map could be used to identify general locations of karst units at 1:50 000, but equivalent-scale bedrock maps or L5 recreation inventory maps should be used for the planning-level inventory.
Planning-level Karst Map at 1:20 000 and possibly 1:50 000 delineating field-checked surface boundaries of karst areas, likely 3-D distribution, discharge area, and subsurface groundwater flow areas and connections.
(for details see Figure 5)
Operational-level Karst Map at 1:5000 or 1:10 000 providing site-specific details on karst unit boundaries, 3-D characteristics, links between surface and subsurface karst and hydrology, identification and karst biota, and air/water quality.
(for details see Figure 6)
Planning-level vulnerability assessment focusing on land and water states of karst ecosystem. Compare with appropriate scale resource maps (e.g., forest cover, fish stream classification).
Operational-level vulnerability assessment for all 4 states of the karst ecosystem. Compare with appropriate scale cutblock and road development maps.
Use findings to assist with forest development plans.
Use findings to assist with management prescriptions for cutblocks and roads.

FIGURE 8 *Summary of linkages between proposed karst inventory levels and vulnerability assessment.*

At the end of the planning-level inventory, a 1:20 000 map should be completed and marked with: the field-checked surface boundaries of the karst areas, the karst catchment/recharge areas (this could include upslope non-karst areas), subsurface flow paths and connections, major surface karst features, cave entrances, and karst hydrological features. The karst areas should be mapped into various polygons with similar intensities of karst development. (Appropriate geological cross-sections would assist in understanding the three-dimensional character of the karst unit and its hydrology.) These inventory data could then be incorporated into a planning-level vulnerability assessment, and compared to maps with proposed forest activities and adjacent (or downstream) resources to assist in management planning and decision making.

Data obtained from the planning level karst inventory could be readily incorporated into the operational-level karst inventory at the desktop phase. Detailed field examination of karst areas (within proposed cutblocks or along roads) should focus on the location and classification of specific surface and subsurface features or resources. Dye tracing could be carried out during the operational-level inventory to answer specific questions on recharge areas or subsurface flows that might have significant management implications. Examples of such questions could include: i) which parts of the recharge area for a karst unit are more critical in terms of impact on downstream fish habitat, ii) what size of buffer should be left on a particular sinking stream, and iii) where will groundwater flows from a particular quarry site go?

At the end of the operational inventory, a 1:5000 or 1:10 000 scale map should be completed and marked with: the karst unit boundaries, overall recharge area for the karst unit (may require a 1:20 000 scale map), local recharge areas for specific sinking streams/insurgence sites, surface karst features (point locations or mapped zones), projected outlines of subsurface cave passages, and subsurface flow paths and conduits. Profiles or cross-sections could be used to display the three-dimensional nature of the karst areas. Data collected during the operational level inventory could be used for an operational vulnerability assessment. This could be done by: i) using and refining vulnerability polygon boundaries developed during the planning vulnerability assessment, ii) developing new map polygon boundaries within a layered GIS system for the various ecosystem sub-states, and iii) incorporating the data into a prescribed field form (see Section 6.4). A risk assessment could then be carried out using the operational vulnerability ratings in conjunction with proposed activities and adjacent or downstream resources.

7.2 Linkages between the Proposed Karst Inventory System and Other Inventory Procedures

Both regional bedrock geological mapping (see SGBM-BC) and 1:250 000 terrestrial ecosystem mapping include data that can be incorporated into the reconnaissance-level karst inventory. However, it is unlikely that these inventories could use the specific data obtained from the reconnaissance-level karst inventory.

Planning- and operational-level karst inventories have a greater number of linkages with other inventory programs (see Figure 9). At least seven complementary inventories were identified:

- Terrain Stability Mapping,

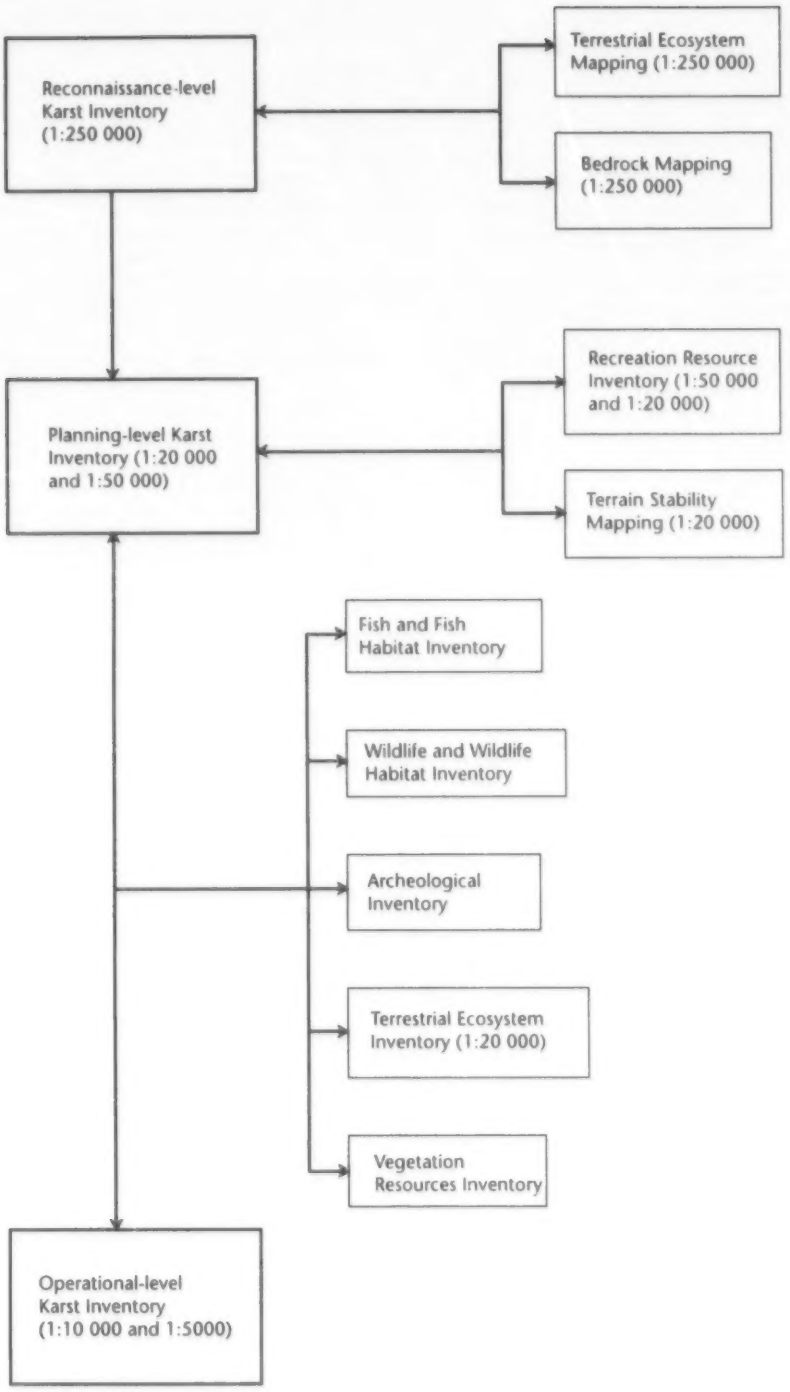

Reconnaissance-level Karst Inventory (1:250 000)
Terrestrial Ecosystem Mapping (1:250 000)
Bedrock Mapping (1:250 000)
Planning-level Karst Inventory (1:20 000 and 1:50 000)
Recreation Resource Inventory (1:50 000 and 1:20 000)
Terrain Stability Mapping (1:20 000)
Fish and Fish Habitat Inventory
Wildlife and Wildlife Habitat Inventory
Archeological Inventory
Terrestrial Ecosystem Inventory (1:20 000)
Vegetation Resources Inventory
Operational-level Karst Inventory (1:10 000 and 1:5000)

FIGURE 9 *Likely linkages between proposed karst inventory levels and other inventories.*

- Terrestrial Ecosystem Mapping,
- Vegetation Resources Inventory,
- Recreation Resource Inventory,
- Archaeology Inventory,
- Wildlife and Wildlife Habitat Inventory, and
- Fish and Fish Habitat Inventory.

Terrain Stability Mapping

Terrain stability mapping identifies unstable and potentially unstable land areas by inventorying the character and distribution of surficial materials, and inventorying active geomorphological processes that can lead to instability. Terrain stability mapping is best linked to karst inventories at the planning scale (see Section 4.3). The planning-level karst inventory would be more cost-effective if it was integrated with terrain stability mapping. Terrain stability mapping is also linked to terrestrial ecosystem mapping in some circumstances. Concurrent terrain stability mapping and terrestrial ecosystem mapping with karst inventories is probably also cost-efficient.

Terrestrial Ecosystem Mapping

Terrestrial ecosystem mapping is used for interpretations related to forest, range, wildlife, soils and biodiversity management. The landscape is stratified into map units based on ecological criteria (e.g., climate, physiography, surficial material, soils and vegetation). This mapping combines biogeoclimatic ecosystem classification and ecoregion classification in order to map homogeneous areas. Terrain ecosystem mapping (at 1:20 000 scale) could be used as a first pass biota stratification for the planning-level karst inventory. It would be both useful and cost-efficient for field personnel to collect information that could be used for karst inventories during terrestrial ecosystem mapping.

Vegetation Resources Inventory

The vegetation resources inventory describes vegetation cover and other non-timber characteristics of the landscape, using the British Columbia Land Cover Classification Scheme (RIC Standard). These inventories identify harvest status, stand treatments, wildfires, insects, and disease, and are used to provide a basis for wildlife habitat mapping. Procedures and standards for ground sampling are described in the RIC publication, *Vegetation Resources Inventory Draft Sampling Procedure*. Linkages exist for the vegetation resources inventory to be conducted concurrently with terrestrial ecosystem mapping. Initial polygon delineation from terrestrial ecosystem mapping can be directly applied to the vegetation resources inventory. The surficial ecological data could also be used within the planning-level karst inventory.

Recreation Resource Inventory

Recreation inventories are initiated and maintained to meet FPC planning requirements and RIC standards. A recreation resource inventory involves identifying, classifying, and recording the types and locations of amenity resources. This inventory actually encompasses the recreation features

inventory, visual resources inventory, visual sensitivity inventory, and recreation opportunity spectrum (ROS) inventory, as well as inventories of rivers, sites, trails, caves, and interpretive forest sites. The recreation resource inventory is normally carried out at a 1:50 000 scale (1:20 000 on Vancouver Island and in the Lower Mainland). Karst features are linked to recreation inventories by a series of recreation feature codes that denote karst/cave areas within L5 polygons. The codes are: K00-cave/karst features, K01-cave, K02-sinkhole, and K03-limestone plateau. Recreation karst information is most useful at the planning-level inventory, where it can be used as base information. However, final planning-level inventory maps could also be used to update recreation inventories.

Archeological Inventory

There are two types of archaeological inventories: Archeological Overview Assessments (AOA's) and Archeological Inventory Studies (AIS's). AOA's can be used at the forest development planning level, and to position AIS's. The AOA is used to estimate or predict an area's potential for archeological resources. The results are used to determine the need for subsequent impact assessments and management studies before the approval of forest development activities. The AIS's are field surveys used to locate and record archaeological sites within a proposed study area. They can provide baseline information on archaeological site locations in a variety of biophysical settings.

AOA's and AIS's must be consistent with the *British Columbia Archaeological Impact Assessment Guidelines* (Apland and Kenny 1994). In addition, AIS's must be consistent with the *British Columbia Archaeological Site Inventory Form Guide*. All work is completed at a scale of 1:20 000 and thus could be readily linked to the planning-level karst inventory, if required.

Wildlife and Wildlife Habitat Inventories

Wildlife and wildlife habitat inventories include broader ecological values that require a comprehensive habitat inventory. These inventories are required to provide information in support of forest development and logging plans, and are designed to produce information that complies with FPC wildlife regulations. The distribution of red- and blue-listed species and habitats at risk, or a particular management concern, can be identified during these inventories. The habitat information is typically derived from species/habitat models in conjunction with terrestrial ecosystem and vegetation resource mapping. When conducting wildlife habitat mapping, methods must follow the RIC standards for ecosystem mapping as set out in the STEM-BC. Priority inventories are carried out in areas of high wildlife value where little information exists, in areas where active planning is in progress, or in areas where species are at risk.[7] Planning- and operational-level karst inventories could be linked to wildlife and wildlife habitat inventories when specific karst-related fauna are identified.

[7] "Species at risk" refers to: any wildlife species that is threatened, endangered, sensitive or vulnerable; any threatened or endangered plant or plant communities requiring protection; and regionally important wildlife.

Fish and Fish Habitat Inventories

Fish and fish habitat inventories provide information about fish distribution and the condition and capability of supporting habitats. The purpose of fish and fish habitat inventories at the planning level is to assist in the compilation of forest development plans, logging plans, and silviculture prescriptions. Intensive inventories at an operational level generate additional information required for managing species and designating habitats at risk. Karst inventories would be linked to these inventories when fish habitats occur within karst areas, or when downstream fish habitats are likely to be influenced by upland karst units.

7.3 Suggestions for Further Work to Refine and Improve the KISP

Further work is required to both refine and improve the preliminary KISP at all three inventory levels, particularly because many of the procedures suggested have not been extensively tested or used. The proposed vulnerability assessment procedure is still in a conceptual form and needs considerable refinement and testing. However, once further developed, it could provide a useful and powerful management tool.

The reconnaissance-level karst inventory could be tested and refined in a number of areas. One primary concern is the use of a numerical rating system that has to be developed into an acceptable province-wide format. A number of carefully selected karst areas (e.g., northern Vancouver Island, Nelson, Prince George) could be chosen and the methodology applied. In addition, work is needed to determine exactly how the biogeoclimatic information could be suitably incorporated into the methodology. GIS data systems should be examined so that information gathering, analysis, and display is completed in a well-organized and systematic fashion.

Of the three karst inventory levels, the planning level (particularly Phases 2 and 3) is the one that probably requires the most testing. Phase 2 requires the mapping of karst areas using a modified terrain mapping methodology. This methodology needs field testing to check that it is both reliable and cost-effective. Phase 3, dye tracing, is a well-recognized procedure for assessing karst hydrology, but it has not been used extensively in forested areas of British Columbia. To demonstrate both the uses and applications of dye tracing in forest management, it is suggested that a series of field trials be carried out in carefully selected representative areas.

The operational-level karst inventory is probably the level at which most work on coastal karst areas has been carried out in the past. However, there are still parts of the methodology that could benefit from testing, including: i) a controlled field trial for the various ground search methods to test them for accuracy, precision, efficiency, and costs, ii) investigating suitable methods for graphical representation of three-dimensional karst data in GIS, and iii) investigating suitable classification schemes and symbology for surface karst and hydrological features.

The karst ecosystem vulnerability methodology could be tested and refined in a number of ways. The schemes developed for the various karst ecosystem states should be expanded to include more details on measurable attributes and examples of site characteristics. At the planning level, the vulnerability assessment procedure should be adapted and applied to polygons obtained from the karst-modified terrain mapping methodology.

The vulnerability assessment at the planning level should be evaluated to see whether it could be used as an effective planning tool. At the operational level, possible options/formats for carrying out the vulnerability assessment should be investigated. For example, would a GIS-based mapping system be effective, would a simple field form format be acceptable, or would a combination of both be required?

One of the principal concerns for the KISP it that it must be developed for all areas of British Columbia. At present, it has been developed primarily on experience and information from coastal forested areas. Some adaptation and refinement will probably be required for forested areas in the interior of British Columbia and, if used in non-forested areas, for alpine and grassland settings.

Another major concern is the management and secure storage of karst inventory information. Appropriate storage of information should be carried out at the various administrative levels (e.g., forest district, forest region, and province). The purpose would be to ensure accessibility only by authorized resource planners, to ensure inventory standardization, and to promote general administrative efficiency. Further investigation is required to assess the data requirements for setting up such a system.

8.0 REFERENCES

Aley, T. and C. Aley. 1993. Delineation and hazard area mapping of areas contributing water to significant caves. Proceedings of the 1993 American Cave Conservation Association, pp. 116–122.

Aley, T., C. Aley, W.R. Elliott and P. Huntoon. 1993. Karst and cave resource significance assessment, Ketchikan area, Tongass National Forest, Alaska. Final report. Prepared for Ketchikan Area of the Tongass National Forest.

Apland, B. and R. Kenny. 1994. British Columbia archeological impact assessment guidelines. B.C. Ministry of Small Business, Tourism and Culture, Archeology Branch, Victoria, B.C. Revised.

Baichtal, J.F. 1997. Application of a karst managment strategy: two case studies from the Tongass National Forest, Southeast Alaska. The challenges of implementation. Paper presented at the 1997 Karst and Cave Management Symposium, Bellingham, Wash. Oct. 1997.

Baitchtal, J.F. and D.N. Swanston. 1996. Karst landscape and associated resources: a resource assessment. USDA Forest Service, Pacific Northwest Research Station, Portland, Oreg. General Technical Report PNW-GTR-383.

British Columbia Forest Service. 1991. Cave/karst management. *In* B.C. Forest Service Recreation Manual, Victoria, B.C. Chapter 13.

Brown, D.W. 1996. British Columbia land use charter in strategic land use planning source book. Commission on Resources and Environment, Victoria, B.C.

Brown, I.C. (editor). 1996. Groundwater in Canada. Geological Survey of Canada. Ottawa, Ont. Economic Geology Report No. 24.

Butrenchuk, S.B. 1991. Gypsum in British Columbia. B.C. Geological Survey Branch. Open File 1991–15.

Doerfliger, N. 1996. Advances in karst groundwater protection strategy using artificial tracer test analysis and multi-attribute vulnerability mapping (EPIK method). Unpublished PhD thesis. Neuchatel University, Switzerland.

Dunham, R.J. 1962. Classification of carbonate rocks according to deposition texture. American Association of Petroleum Geologists, Memoir Number 1, pp. 108–121.

Eberhard, R. 1996. Inventory and management of karst in the Florentine Valley, Tasmania. Forestry Tasmania, Hobart, Tasmania.

Ecock, B.A. 1984. The hydrology of an alpine karst: White Ridge, Vancouver Island. Unpublished MSc thesis. McMaster University, Hamilton, Ont.

European Commision Report. 1995. Karst groundwater protection. Report EUR 16547 EN, Luxembourg.

Fischl, P. 1992. Limestone and dolomite resources in British Columbia. B.C. Geological Survey Branch. Open File 1992–18.

Folk, R.L. 1962. Spectral subdivision of limestone types. American Association of Petroleum Geologists, Memoir Number 1, pp. 62–84.

Ford, D.C. 1987. The effects of glaciation and permafrost upon the development of karst in Canada. Earth Surface Processes and Landforms, 12:507–521.

Ford, D.C. and P. W. Williams. 1989. Karst geomorphology and hydrology. Unwin Hyman Ltd., London, U.K.

Gascoyne, M., D.C. Ford and H.P. Schwarez. 1981. Late Pleistocene chronology and paleoclimate of Vancouver Island determined from cave deposits. Canadian Journal of Earth Sciences 18:1643–1652.

Glasco, D. 1992. Cave hunting: using remote sensing to find karst terrains, features and caves. Honors Paper Submitted as a Requirement for GECA: Remote Sensing. George Mason University, Fairfax, Va.

Gunn, J. 1995. Environmental change and land management in the Cuilcagh Karst, Northern Ireland. *In* Geomorphology and land management in a changing environment. D.F.M. McGregor and D.A.Thompson (editors). John Wiley and Sons, London, U.K. pp. 196–209.

Harding, K.A. and D.C. Ford. 1993. Impacts of primary deforestation upon limestone slopes in northern Vancouver Island, British Columbia. Environmental Geology 21: 137–143.

Harza Northwest Incorporated. 1995. Karst vulnerability assessment report, Phase II site specific verification study, Lab Bay environmental impact assessment, Prince of Wales Island, Alaska. 1995. Prepared by Harza Ltd. and the Ozark Underground Laboratory for the USDA Forest Service, Tongass National Forest.

Hebda, R.J. 1995. The paleoecological significance of Pellucidar Cave, north Vancouver Island. Royal British Columbia Museum, Victoria, B.C. Draft report.

Huntoon, P.W. 1995. The case for upland recharge area protection in the Rocky Mountain karsts of the western United States. Proceedings of the International Symposium on Karst Water and the Environmental Impacts. Antalya, Turkey. Sept. 1995.

Interior Karst Consultants. 1997. Cave and karst inventory of the Herrick Watershed, 1997-98. Unpublished planning document prepared for the Prince George Forest Region and Forest Renewal BC.

Jennings, J.N., 1971. An introduction to systematic geomorphology. Vol. 7. The MIT Press, Cambridge, Mass.

Kiernan, K. 1990. Soil and water degradation in carbonate rock terranes. Australian Journal of Soil and Water Conservation 3(4): 26–33.

Marshall, W. 1997. Evolution of cave/karst management in British Columbia's Provincial Forests. B.C. Ministry of Forests, Victoria, B.C. Unpublished.

Nossin, J.J. 1989. SPOT stereo interpretation in karst terrain, southern Turkey. ITC (International Institute for Aerospace Survey and Earth Sciences) Journal 1989-2:79–91.

Province of British Columbia. 1981. A statement of Crown land cave policy and administration. B.C. Ministry of Lands, Parks and Housing, Parks and Outdoor Recreation Division, Victoria, B.C.

Rollins, J. 1992. Management considerations for caves and related karst features in the southern Canadian Rockies. Submitted to the Faculty of Environmental Design in partial fulfillment of the requirements for the Degree of Masters of Environmental Science. University of Calgary, Calgary, Alta.

_____. 1997. Caves and related karst areas of the northern Canadian Rockies. Unpublished Report. Contact Jon Rollins at 2512 19 St. N.W., Calgary, Alta., T2M 3V4.

Rollins, R. 1995. Caves of the Rocky Mountains. Research Links, Vol. 3, No. 1, Spring 1995. Parks Canada, Alberta and Pacific-Yukon Regions.

Stokes, T.R. 1994. 1:250,000 cave/karst potential maps of the Vancouver Forest Region. Contract completed for the Vancouver Forest Region. Set of 26 maps with accompanying report.

_____. 1995a. 1:250,000 cave/karst potential maps of the Prince Rupert Forest Region. Contract completed for the Prince Rupert Forest Region. Set of 10 maps.

_____. 1995b. Evaluation of coastal British Columbia for potential cave and karst terrain: a regional rating system. Abstract in GAC-MAC Annual Meeting, Victoria, B.C. p. A101.

Stokes T.R., N. Massey, and P. Griffiths. 1997. Digital cave/karst potential mapping in northern Vancouver Island: a strategic forestry planning tool. Poster presented at the 1997 Karst and Cave Management Symposium, Bellingham, Wash. Oct. 1997.

Sweeting, M.M. 1973. Karst landforms. Columbia University Press, New York, N.Y.

Trenhaile, A.S. 1990. The geomorphology of Canada. Oxford University Press, Toronto, Ont.

USDA Forest Service. 1997. Tongass National Forest land and resource management plan. Alaska Region.

Viles, H.A. 1988. Biogeomorphology. Basil Blackwell, New York, N.Y.

White, W.B., D.C. Culver, J.S. Herman, T.C. Kane, and J.E. Mylroie. 1995. Karst lands. American Scientist 83:450–459.

9.0 GLOSSARY

Anhydrite	A mineral; anhydrous calcium sulphate.
Anthropogenic	Caused by or resulting from the acts of humans.
Biogenic	Of biological origin; organic.
Biospace	The separated or interconnected network of "spaces" as air- or water-filled cracks, pipes, vertical channels, tubes, voids or microcavities, horizontal conduits, and larger cavities, including caves, that are inhabited by invertebrates, including in the interstitial medium and saturated zone.
Biota	All living organisms of an area, taken collectively.
Calcareous	Containing calcium carbonate; from the Latin word *calcarius*, meaning "of lime."
Calciphilic	Biota that prefers calcareous soils or rock.
Calcite	A mineral composed of calcium carbonate, like aragonite but differing in crystal form; the principal constituent of limestone.
Carbonate	A salt or ester of carbonic acid, such as calcium carbonate. A rock consisting mainly of carbonate minerals, such as limestone or dolomite.
Catchment	The surface area drained by various-sized watercourses.
Caver	A person who explores caves as a hobby or for recreation.
Chert	Light-cream or grey to black rock composed of silica, found occurring as nodules or layers in limestone, or as a replacement of limestone.
Closed depression	A general term for any enclosed topographic basin having no external drainage, regardless of origin or size.
Conductivity	A measure of the ability of water to conduct electricity.
Conduit	A subterranean stream course filled completely with water and always under hydrostatic pressure.
Cutblock	A specific area, with defined boundaries, authorized for timber harvest.

Doline	A basin or funnel-shaped hollow in limestone ranging in diameter from a few metres to a kilometre, and in depth from a few to several hundred metres. May be distinguished as "solution" or "collapse" if precise origin is known.
Dolomite	A mineral composed of calcium magnesium carbonate. Rock chiefly composed of the mineral dolomite. Also called dolostone.
Dry valley	A valley that lacks a surface water channel.
Epikarst	The upper zone of a karst area that extends downward as sinkholes, fractures, fissures, and other surface karst features to where the natural porosity of the bedrock is located. Epikarst can range from almost non-existent to tens of metres deep.
Evaporite	A sediment that is deposited from aqueous solution as a result of extensive or tota! evaporation of the solvent.
Exsurgence	Point at which an underground stream reaches the surface if the stream has no known surface headwaters.
Grike, gryke	A vertical or subvertical fissure in a limestone pavement developed by solution along a joint.
Gypsum	A mineral; hydrated calcium sulphate.
Insurgence	The point at which water sinks into the ground.
Interbed	A typically thin bed of rock material alternating with contrasting thicker beds.
Karren	Channels or furrows, separated by ridges, resulting from solution of carbonate rock on the surface or under soil layers.
Karst	A terrain, generally underlain by limestone, in which the topography is formed chiefly by the dissolving of rock, and which is commonly characterized by karren, closed depressions, subterranean drainage, and caves.
Karst bridge	A natural bridge or arch in limestone.
Karst canyon	A natural steep-sided canyon in limestone.
Karst catchment	The subaerial surfaces upon which water contributes to the recharge of a karst aquifer. Also known as true catchment or geologic catchment.
Karst hydrology	The drainage phenomena of karstified limestones, dolomites, and other slowly soluble rocks.

Karst spring	A spring emerging from karstified limestone. See also exsurgence and resurgence.
Karstification	Action by water, mainly chemical but also mechanical, that produces features of a karst topography, including such surface features as dolines, and karren, and such subsurface features as caves and shafts.
Limestone	A sedimentary rock consisting mainly of calcium carbonate.
Limestone pavement	A bare plane surface of limestone, parallel to the bedding, commonly divided into blocks (clints) by solutionally widened joints (grikes), and pitted by solution pans.
Lithology	The physical characteristics of a rock, generally as determined megascopically or with the aid of a low-power magnifier. The microscopic study and description of rocks.
Marble	Limestone recrystallized and hardened by pressure and heat.
Microcavity	Predominantly an air-filled cavity, usually referring to voids in the epikarstic region of the unsaturated zone and considered to include all cavities not large enough to be defined as caves.
Paleontology	The study of life of the past by interpreting fossil remains of plants and animals.
Recharge	The process involving the input or intake (absorption) of water into the zones of saturation in karst aquifers; also relates to the quantity of water added to the saturation zone.
Resurgence	The point at which an underground stream reaches the surface and becomes a surface stream; the term is reserved for the re-emergence of a stream that has earlier sunk upstream. The term exsurgence is applied to a stream without known surface headwaters.
Sink, sinkhole	General terms for closed depressions. They may be basin, funnel, or cylindrical shaped. Also closed depression, doline, swallet, swallow hole.
Sinking creek (stream)	A small stream that disappears underground. See also swallet.
Solution	With reference to karst, the chemical alteration of bedrock from the solid to the liquid state through combination with water.

Speleological	Pertaining to the scientific study, exploration, and description of caves and related features.
Speleologist	A scientist engaged in the study and exploration of caves, their environment, and their biota.
Speleothem	A secondary mineral deposit formed in caves, such as a stalactite or stalagmite. Also known as a cave formation.
Stratigraphic	Pertaining to the formation, composition, sequence, and correlation of stratified rocks.
Swallet	A place where water disappears underground in a limestone region. A swallet may refer to water loss in a streambed even though there is no depression. A swallow hole generally implies water loss in a closed depression or blind valley. See also sinking stream.
Troglobite	An animal living permanently in the dark zone of a cave and unable to live outside the cave environment.
Understorey	Any plants growing under the canopy formed by other plants, particularly herbaceous and shrub vegetation under a tree canopy.
Uvala	Large closed depression formed by the coalescence of several dolines; compound doline.
Vadose	Pertaining to the zone where voids in the rock are partly filled with air and through which water descends under gravity.

DELINEATION AND HAZARD AREA MAPPING OF AREAS CONTRIBUTING WATER TO SIGNIFICANT CAVES

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ABSTRACT

The recharge area for a cave is that area which contributes water to the cave. In some cases the recharge area is little more than the land which overlies the cave. However, in many cases (and especially when the cave contains streams or lakes) the recharge area may encompass several square miles.

Groundwater tracing is a fundamental tool for recharge area delineation. The general approach is to introduce fluorescent tracer dyes at points where surface waters sink into the groundwater system and then sample for these dyes at springs, significant caves, and other relevant points.

Hazard area assessment and mapping is a management approach for identifying and characterizing those areas which pose the greatest water quality threats to significant caves. Hazard area delineation integrates the hydrologic functioning of particular units of land with the uses of those lands. This paper will help resource managers understand the benefits of recharge area delineations and hazard area mapping and understand characteristics of technically sound investigations.

INTRODUCTION

The area which contributes water to a cave is called the recharge area. With few exceptions, identifying the recharge area for a significant cave represents fundamental management information. Recharge area delineations are particularly important for caves with important aquatic cave faunas.

The purpose of this paper is to provide resource managers with a workable understanding of how cave recharge areas are delineated and how hazard area mapping is done. While there is no single "right" way there are clearly many ineffective or undesirable ways to accomplish this work.

Cave Mapping and Topographic Studies

While cave maps can provide useful data, they seldom provide an adequate basis for recharge area delineation. We sometimes see assumptions that the area overlying a cave plus some arbitrary narrow "buffer zone" on the order of 100 to 300 feet is the sole source of recharge waters for that cave. This assumption is questionable (and often wrong) even when the cave contains neither streams nor lakes, and where only drippage waters are present. The assumption is frequently wrong even when the dip the bedding is taken into account. A major reason that this approach is often in error is that flow paths in the epikarstic zone (the weathered and corroded zone beneath the soil) are highly complex, may be dramatically different from the dip, and may involve lateral water movement over substantial distances.

Water infiltrates the epikarstic zone more rapidly than it infiltrates beneath it; this results in appreciable water storage in the epikarstic zone and lateral water movement through the zone since lateral permeability is routinely much greater than vertical permeability.

It is sometimes assumed that groundwater flow directions and divides are identical, or very similar to, surface flow directions and topographic divides. In our experience this assumption is commonly false. An exception could be a cave in the bottom of an intermittent surface stream channel, although such caves may also receive water from points not tributary to the surface stream. Even when it appears that the recharge area for a cave may be estimated from surface features, actual delineation studies should be conducted for verification.

Equipotential maps, which are contour maps of the water table elevation, can be developed for areas. In most (but not all) karst areas these maps are not of great utility in delineating cave recharge areas. One reason is that the data points are generally widely scattered and poorly distributed; the resulting maps are thus gross generalizations. Well depths vary substantially in many karst areas, and water level elevations are significantly affected by the geologic units in which the well is developed. In one cave area we routinely encountered differences in water level elevations of over 100 feet between nearby wells 125 feet deep and those 300 feet deep. Differences are generally not this great, yet the differences are commonly sufficient to readily produce incorrect interpretations.

Groundwater Tracing

Realistic recharge area delineation requires groundwater tracing. The tracing is generally conducted with fluorescent tracer dyes. Other tracing agents exist, but their use is substantially more difficult than tracing with the fluorescent dyes. Some of the other tracing agents, such as sodium chloride, are likely to create adverse impacts. Groundwater tracing techniques are described in detail by Aley and Fletcher (1976) and by Aley et al. (1992). There have been major improvements in analytical techniques since the Aley and Fletcher (1976) publication.

The most effective and most commonly used tracer dye is sodium fluorescein (Acid Yellow 73, Color Index [ICI] Constitution Number 45350). It is commonly simply called fluorescein in the United States; it is

sometimes called uranine (especially in Europe). It is most commonly sold in a powder form which has a strong reddish color. When added to water the dyed solution is a brilliant yellow-green color. Visual detectability is significantly affected by background color in the dyed water and other factors. An experienced observer can commonly detect fluorescein in the field in concentrations as low as about 30 micrograms per litre (parts per billion).

The concentration of fluorescein in dye mixtures sold by various supply houses varies substantially. Some of the liquid mixtures contain less than 5% fluorescein. Powder mixtures generally contain more fluorescein than liquid mixtures, but they also vary widely. In order to achieve a uniform product and, in some cases, to enhance the ease of dyeing a product, it is conventional to add diluents (cutting agents) to technical grade dyes. This is standardization, not adulteration. The diluent most commonly used with fluorescein is sodium sulfate.

Rhodamine WT (Acid Red 388) is also a commonly used tracer dye. Rhodamine WT should not be confused with other Rhodamine dyes; some of the other Rhodamine dyes have undesirable properties. Rhodamine WT is commonly sold as a 20% dye solution. When added to water the dyed solution is pinkish orange. As with fluorescein, visual detectability of Rhodamine WT is affected by background color in the dyed water and other factors. An experienced observer can commonly detect Rhodamine WT in the field in concentrations as low as about 50 micrograms per litre (parts per billion).

Various optical brighteners have also been used in groundwater tracing. These are pale blue fluorescent dyes commonly used in laundry soaps and detergents to make "whites appear whiter." Because of their use in soaps and detergents the optical brighteners may already be present in cave waters; this limits their utility for recharge area delineation studies. However, sampling for background concentrations of optical brighteners can be useful in indicating sewage contamination of the cave waters (Aley 1985). We find background sampling for optical brighteners to be a very useful approach during a recharge area delineation study. It should be noted that the absence of background optical brighteners in cave waters may result from their adsorption onto fine textured soils; sewage effluents may be present even if optical brighteners are absent.

Direct Yellow 96 (Diphenyl Brilliant Flavine 7GFF) is a fluorescent yellow dye which has been successfully used in a number of groundwater traces in Kentucky. Other fluorescent dyes which have received some use in the United States include Pyranine (CI 59040; CI solvent green 7, D&C green 8); Lissamine FF (CI 56205; CI acid yellow 7); and Eosine Sodium (CI 45380). Amino G Acid, a dye intermediary, has also been used. Anyone competently using any of these dyes will almost certainly also be using fluorescein, Rhodamine WT, and probably optical brighteners.

Of the four most commonly used dyes, fluorescein is generally the best for groundwater tracing and Rhodamine WT is the second best. Fluorescein is more subject to destruction or alteration in sunlight than is Rhodamine WT, optical brighteners, or Direct Yellow 96. Significant dye losses by adsorption onto charged soil particles can occur with any of the dyes; in our experience dye losses to adsorption increase in the order of

fluorescein, Rhodamine WT, optical brighteners, and Direct Yellow 96. Use of optical brighteners and Direct Yellow 96 is unlikely to be successful in groundwater systems where appreciable adsorptive losses occur. Other considerations are also involved in the selection of the dye or dyes to use.

There are sometimes sources of background fluorescence which can interfere with the detection of tracer dyes. Additionally, the tracer dyes (or similar dyes) may be components of compounds already present in the area. Fluorescein is used in a few household products and as the coloring agent in antifreeze. It can sometimes be detected in runoff waters from parking lots and city streets. Pyranine is used in more household products than fluorescein; these dyes cannot be readily separated visually or with a fluorometer, but they can be separated with a spectrofluorophotometer operated with a synchronous scan protocol. A dye which cannot be fluorescently distinguished from Rhodamine WT (it is probably Rhodamine B) is used as the coloring agent in many hydraulic fluids. It is routinely present in the waste water from manufacturing plants which use hydraulic equipment. Additionally, Rhodamine B has also been used to color seed corn to prevent it from accidentally being fed to livestock.

Cumulative samplers capable of absorbing passing dyes are commonly used in recharge area delineation studies. Activated carbon samplers are used to adsorb dyes such as fluorescein, Rhodamine WT, and some of the less commonly used dyes. Cotton samplers are used to adsorb optical brighteners and Direct Yellow 96 "grab samples" of water can be collected for dye detection, but the frequency of sampling necessary to insure that a pulse of tracer dye is not missed limits the general utility of this approach. Grab samples of water collected simultaneously with the collection of activated carbon samplers can provide valuable data on actual dye concentrations at particular points in time if the analysis protocol is capable of providing credible quantitative results.

Cumulative samplers are typically collected and new samplers placed about once a week, although the frequency can be varied depending upon the nature of the study. Activated carbon samplers are eluted with a strong base, alcohol, and water solution. Moderate to large concentrations of fluorescein can be detected visually in the eluting solution. Visual detection of Rhodamine WT in the eluting solution is difficult; this dye should not be used in groundwater tracing unless analytical equipment is available. Simultaneous tracing with fluorescein and Rhodamine WT can be done with the use of a spectrofluorophotometer operated in a synchronous scan mode. It should not be attempted with a fluorometer since large concentrations of one dye will create an apparent detection of the other dye with this type of instrument.

Cotton samplers are washed with jets of clean water and then examined either under an ultraviolet light or in an appropriate analytical instrument. Experience and care are essential in visual analysis. Optical brighteners and Direct Yellow 96 can mask one another unless both are present in large concentrations. These dyes can be used simultaneously if analysis is done with a spectrofluorophotometer operated in a synchronous scan mode.

The common groundwater trace utilizes cumulative samplers. Background sampling, prior to any introduction of tracer dyes, is generally conducted to demonstrate the absence of fluorescence interference or to characterize the magnitude of the interference. The extent of background sampling is largely determined by the nature of land use in the area.

A well designed delineation study for an important cave is characterized by thorough field work to identify potential dye injection sites and caves or springs through which the injected dye may subsequently pass. Simply studying topographic maps and aerial photos alone will seldom be sufficient. These approaches generally miss many important springs. Groundwater tracers seem to have a propensity to discharge from springs that were not sampled. Some of the missed springs may be in the channel of surface streams. As a result, surface streams must be sampled to address this possibility. Multiple sampling stations are routinely needed along surface streams since tracer dyes deteriorate and are adsorbed as they are transported down the stream channel. In delineation studies, a trace that goes to the "wrong" spring provides valuable data for the delineation of the cave or spring of concern. It is always better to know where the trace went than to simply know where it did not arrive. This is not always possible; an example would be an area where many springs are beneath the surface of large lakes.

The easiest sites for injecting tracer dyes are points where water always or almost always sinks into the groundwater system. Sites near roads, on public land, or on property of landowners known to be friendly are always nice. The easiest sites are frequently not those most useful for a good delineation study. The good delineation study must gather the data needed rather than the data that are more easily available.

A good delineation study must be dynamic; one should seldom plan more than one or two traces in advance. The results from one trace must be incorporated into the planning for the next. Tracing should take advantage of weather conditions. Some highly desirable tracer injection sites have flowing water only a few days out of the year. Unless one can haul substantial volumes of water, these sites must be used when the water is present. Sometimes one can place the tracer dye where it will enter the water the first time flow occurs; this must be done very carefully.

Another characteristic of a good delineation study is that many of the dye injection sites are located in areas where contaminants enter (or might enter) the groundwater system. We routinely select injection sites which receive waters from dumps and landfills; sewage and sewage effluent discharges; commercial and industrial operations; highways, railroads, and product pipelines; and major sources of animal wastes. The failure to recover dye from such traces in the cave of concern is always an important finding; however, important caves are not immune to impacts from these types of land uses.

A good delineation study should include groundwater traces which are recovered in the cave of concern plus some traces which are recovered at sites other than the cave. If all of the traces are recovered in the cave of concern you have probably not identified the boundary of the recharge area.

Water that enters the karst groundwater system at a particular point does not always flow only to one cave or spring. The flow may be to two or more caves or springs. In one study Aley (1988) found radial groundwater flow throughout a large area in northwestern Arkansas. Not only can the flow be shared among several caves or springs, but the relative quantity moving to each site can vary with flow rates and other groundwater conditions.

We often find that a particular cave (or spring) has some recharge areas which contribute waters only to that cave. Often there are some recharge areas which share water between the cave of concern and other caves or springs. The total recharge area includes both the exclusive recharge area and the shared recharge area. Where feasible, each should be delineated separately and their hydrologic interactions characterized. Shared recharge areas are commonly located near recharge area boundaries; however, distributaries can exist closer to the discharge points for the groundwater system. An illustration of distributaries is provided by the springs which drain the main stream in Tumbling Creek Cave, Missouri. These springs extend for 2,000 feet along Big Creek; none of these springs is more than a mile from the cave stream.

Identification of shared recharge areas routinely requires more comprehensive sampling, good analytical approaches, and project direction by experienced groundwater professionals. Some shared recharge areas deliver water to a cave of concern only during moderate to high flow conditions. Fantastic Caverns near Springfield, Missouri is an illustration of this condition. During low flow conditions the recharge area comprises about 7 square miles. During high flow conditions the recharge area comprises about 20 square miles; at least six springs share portions of this recharge water.

Even a small cave stream may have a large recharge area because of shared recharge areas. Fire Hydrant Cave on the Current River in Missouri is an illustration. This cave shares water with Pulltite Spring and other springs in the area. While the mean flow rate of this spring is relatively small, dye injected in a losing stream segment of Big Creek 13.1 miles straight line distance from the cave was recovered in the cave.

How large are recharge areas for significant caves likely to be? This is a bit like asking the length of a typical piece of string, yet resource managers concerned with potential recharge area delineation investigations need some understanding of the size of areas likely to be involved.

The caves with the largest recharge areas are generally those which contain cave streams or lakes. As a general rule, the greater the mean annual flow of water through the cave the larger the recharge area. If a recharge area is shared by multiple caves and springs the recharge area is likely to be larger than if the cave has an exclusive recharge area. Caves which receive recharge waters from a significant surface stream have recharge areas which include the entire topographic basin of the stream upstream of the recharging point plus any other areas contributing water to the cave stream.

We have delineated the recharge areas for about 25 caves in seven states. Six biologically significant caves had recharge areas of 0.2 to 2.5 square miles; none of these received recharge waters from any appreciable surface

streams. Six other biologically significant caves had recharge areas of 7 to 24 square miles; all but two of these involved either appreciable surface streams or recharge areas shared with other caves or springs. Caves in the Western United States do not necessarily have larger or smaller recharge areas than caves in the Midwest or East.

Hazard Area Mapping

The hydrologic functioning of the land is not uniform. The hydrologic impacts of land use are also not uniform. It is clear that the combined impacts of these conditions on a cave or spring are also variable. Because of these conditions we can develop maps which depict qualitatively different groundwater quality risks posed to a significant cave. This is the foundation for a karst-specific approach which we call hazard area mapping.

We initially developed the approach in 1976 for use in recharge area delineation studies for major springs on the Ozark National Scenic Riverways in Missouri (a National Park unit). We have subsequently applied the approach in many of the delineation studies we have conducted over the last 15 years, and believe it to be a very useful management tool. It has been applied elsewhere in Missouri and in Arkansas, Oklahoma, Wyoming, Kentucky, and Alabama.

A nationally used mapping approach for assessing groundwater contamination risks was developed by the National Water Well Association and the U.S. Environmental Protection Agency (Aller et al. 1987) and is called "DRASTIC." It is a useful approach, but is neither a karst-specific nor a cave resource–sensitive approach. The DRASTIC approach demonstrates that karst areas are readily subject to groundwater contamination but does not provide for more detailed discrimination nor for integrating land use conditions.

We develop somewhat different criteria for hazard area classes for each region (and sometimes for each cave) studied. We typically use three or four categories, although one or more may be absent in particular recharge areas. In a typical hazard area mapping the categories will include low, moderate, high, and extremely high groundwater contamination hazard categories. Situations associated with the higher risk categories include:

1) Areas in close proximity to the cave.
2) Sinkhole areas, losing stream segments, and areas within 300 feet of mapped fracture traces and lineaments.
3) Localized areas where substantial volumes of water enter groundwater.
4) Areas with shallow or very rocky soils.
5) Areas where land uses of concern exist or are likely to exist. Point sources are routinely identified, assessed, and shown on the maps with an index number.
6) Areas which exclusively recharge the cave of concern.

SUMMARY OF GOOD RECHARGE AREA STUDY CHARACTERISTICS

1) The study should be conducted by, or be under the technical direction of, a karst hydrologist who has successfully conducted previous recharge area delineation studies. A person who has previously conducted groundwater traces does not automatically qualify since recharge area delineation and hazard area assessments requires more than simple groundwater tracing. However, the person directing the study should have background or experience in groundwater tracing. Once a year the National Water Well Association offers a week-long professional short course entitled "Practical Karst Hydrogeology with Emphasis on Ground Water Monitoring." This course provides the type of background needed to supplement the conventional background of most groundwater hydrologists. Recharge area studies lie well outside the field of expertise of the typical registered geologist or engineer.
2) Thorough field reconnaissance precedes the start of groundwater tracing. Background sampling is conducted before tracer dyes are injected. Numerous sampling stations are established to insure that the injected dyes are recovered. Dyes appropriate to conditions in the study area are selected and the quantities used are adequate to insure that the failure to recover dye at the cave of concern is credible evidence that a hydrologic connection does not exist. Depending upon conditions, adsorptive losses may cause the failure of groundwater traces conducted with Direct Yellow 96, optical brighteners, and Rhodamine WT.
3) The delineation study should be adequate to detect and assess recharge areas which the cave of concern shares with other caves or springs. The good study will not be limited to just the simple and easy groundwater traces, but will instead include traces from areas where data are needed. The good study will routinely conduct traces to assess sites which pose potentially significant water quality threats to the cave or spring being studied. The study will be dynamic; the results from previous traces must be incorporated into the planning for those subsequently conducted.
4) State of the art analysis for tracer dyes uses a scanning spectrofluorophotometer operated with a synchronous scan protocol. Successful groundwater tracing can be done using visual and fluorometric methods, but these approaches slow the tracing program because of dye interferences and the necessity of using more dye to insure positive results. Increasing the quantity of dye increases the duration of the dye pulse and, in turn, the time between traces. Field time is generally the most expensive part of a recharge area study. In our experience, state of the art analysis generally maximizes the number of groundwater traces conducted; it also produces the most credible results. Several firms have this type of equipment; at least two of these firms will routinely conduct dye analysis work on samples shipped to them. Similar equipment exists at a few universities or other state agencies, yet experienced operators and acceptable protocols for dye analysis often limit the utility of this equipment.
5) Hazard area assessments and the development of hazard area maps should be a routine component of recharge area delineations.

Aley, Thomas. 1985. Optical brightener sampling; a reconnaissance tool for detecting sewage in karst groundwater. Hydrological Sci. and Tech. Short Papers, Vol. 1:1, pp. 45–48.

Aley, Thomas. 1988. Complex radial flow of groundwater in flat lying, residuum-mantled limestone in the Arkansas Ozarks. Proc. Second Conference on Environmental Problems in Karst Terranes and Their Solutions. Assoc. of Ground Water Scientists and Engineers, pp. 159–170.

Aley, Thomas and Mickey W. Fletcher. 1976. The water tracer's cookbook. Mo. Speleol., Vol. 16:6, pp. 1–32.

Aley, Thomas, James F. Quinlan, Calvin Alexander, and H. Behrens. 1992 (in preparation). The joy of dyeing; a compendium of ground water tracing techniques. Association of Ground Water Scientists and Engineers.

Aller, Linda, Truman Bennett, Jay H. Lehr, Rebecca J. Petty, and Glen Hackett. 1987. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. U.S. EPA Document 600/2-87-035. 455 p. + maps and appendix data.

DYE TRACING IN FORESTED KARST TERRAIN: A CASE STUDY ON VANCOUVER ISLAND, BRITISH COLUMBIA

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Abstract: This paper presents the findings of a groundwater dye tracing study that was carried out in the Glory'Ole Cave/Karst Management Area (GCMA) of Northern Vancouver Island, British Columbia. The objectives of the project were to delineate the groundwater flow paths and recharge areas of the GCMA, and to demonstrate how this information could be used to assist in forest management. Four fluorescent dyes (fluorescein, rhodamine WT, eosine, and pyranine) were simultaneously injected into flowing water at four different locations: three sinking streams and a surface stream. Charcoal samplers and grab water samples were taken from springs and streams at lower elevations and analyzed for the presence of dyes. All four dye traces were detected at the Tsulton Rising, the principal discharge point for groundwater flow in the GCMA. Most of the non-karst recharge areas upslope of the GCMA contribute to the groundwater discharge at Tsulton Rising. Careful forest management planning and prescriptions are required in these recharge areas to protect water quality and quantity.

1 INTRODUCTION

Karst terrain is the three-dimensional landscape that develops from the weathering of soluble bedrock (Fig. 1). These bedrock types primarily include carbonates such as limestone and dolomite, or evaporites such as gypsum and halite. It has been well documented that karst terrain (or systems) function very differently in geology, hydrology and biology than non-karst, and that karst exhibits a range of significantly different values (Ford and Williams 1989; White et al. 1995). Karst terrain, derived predominately from limestone and dolomite, underlies many of the forested areas of British Columbia (Fig. 2). On Vancouver Island, coastal temperate rainforests occur in conjunction with some of the most well-developed karst terrain and largest cave systems in both British Columbia and Canada (Griffiths 1991). Industrial forestry activities on karst areas can have significant impacts on karst recreational resources, karst flora and fauna, karst soils, karst surface features and karst hydrology (Stokes 1996; Baichtal in press; Baichtal and Swanson 1996; Kiernan 1993). On

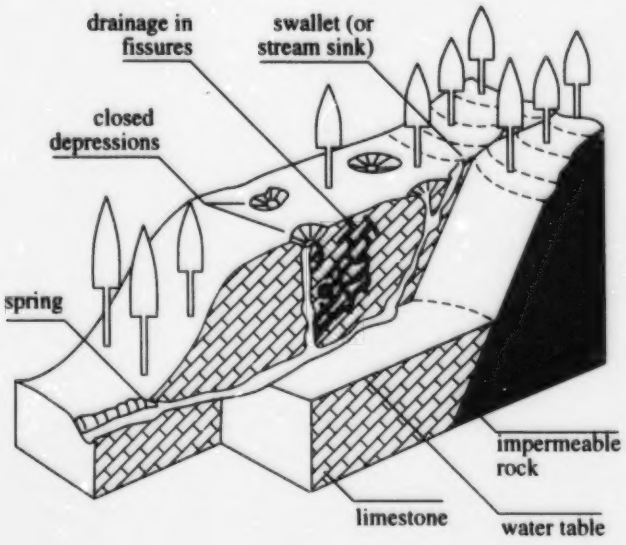


FIGURE 1 *The three-dimensional karst landscape. (Adapted from Cooke and Dornkamp 1990.)*

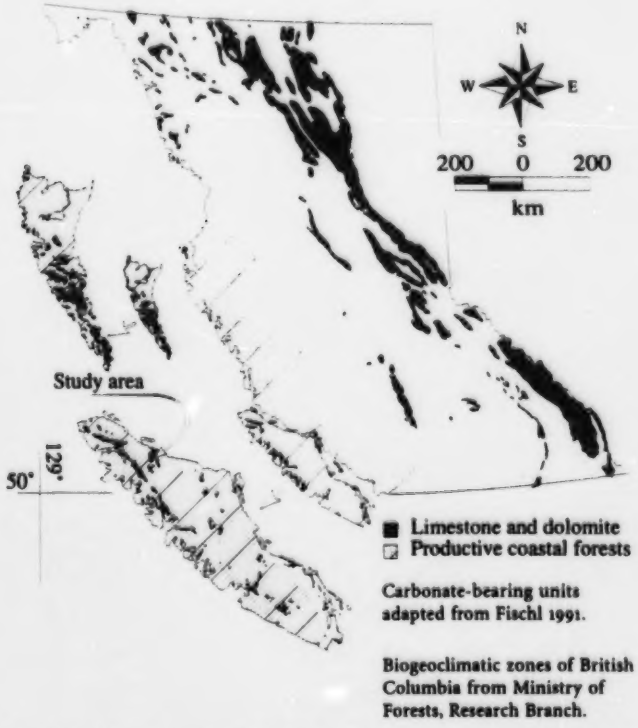


FIGURE 2 *Location of study area within British Columbia and the regional distribution of carbonate bedrock and productive forested zones.*

Vancouver Island, past forest management practices on karst terrain have focused on the identification and protection of significant caves and karst features (B.C. Ministry of Forest 1994). Recent work by the Research Branch of the B.C. Ministry of Forests is focused on a broader ecosystem approach to karst management (B.C. Ministry of Forests 1997).

Karst hydrology, one of the fundamental components of the karst ecosystem, requires careful investigation, as changes to the quality and quantity of upstream karst waters can have significant impacts downstream (e.g., drying and flooding of caves, altering sensitive microclimate and habitats, and the clogging of subsurface conduits with debris). The hydrological system in karst is significantly different from non-karst as much of the system is subsurface, with recharge areas that commonly do not follow topographic divides. Groundwater flows within karst have the potential to rapidly transmit water through bedrock conduits, and to provide groundwater storage in less permeable, highly fissured bedrock volumes (e.g., in epikarst areas). Hence, karst hydrological systems can be characterized as highly variable and are difficult to predict from surface features and topography.

Subsurface investigation of karst hydrological systems can be carried out remotely using dye tracing. Dye tracing is a well accepted and practiced technique that has been used successfully to track the dispersal of contaminants, delineate recharge areas for springs, determine groundwater flow paths, and identify discharge sites (Aley and Aley 1993; Doerfliger 1996). Dye tracing has also been used in the forested karst terrain of southeast Alaska as one of the tools for karst vulnerability mapping (U.S. Forest Service 1996). The basic concept of a dye trace test is simple. A fluorescent dye is injected into an insurgence (e.g., a sinking stream), and then sampled at likely exsurgent sites (e.g., springs). Typical dyes that are used include fluorescein, rhodamine WT, eosine, and pyranine, These dyes are all considered environmentally safe at the concentration levels used for testing (Field et al. 1995; Smart 1984). Sampling for dyes can be carried out by either grab water samples or by charcoal samplers which accumulate traces of the dye over a predetermined period of time. The charcoal samplers are 4 g of activated carbon granules sealed in a fibre mesh packet. Both the elutant from the charcoal samplers and grab water samples can be analyzed with a spectrofluorophotometer. Each of the dyes has a different and diagnostic excitation peak wavelength, with pyranine, fluorescein, eosine, and rhodamine WT having peaks of 502, 512, 535, and 563 nanometres, respectively. Dye concentrations in samples are calculated by comparing the area within the excitation peak to a standard of known dye concentration. Detection limits vary among the dyes, but they are all within the parts per trillion range.

2 STUDY AREA

The Glory'Ole Cave/Karst Management Area (GCMA) was proposed as a study area by the Port McNeill Forest District to test the applicability of dye tracing as a forest management tool. The GCMA was considered a suitable study area because of its cave/karst exploration history, its significant cave/karst resources, and its past and present forestry activities. The general objectives of this project were to determine:

1. The principal groundwater flow paths and likely recharge areas for known springs in the GCMA;
2. What dye tracing methods and dyes are most applicable to conditions on northern Vancouver Island; and
3. How dye tracing could play a role in assisting forest management decisions.

Two site-specific objectives were: i) to determine the groundwater source for the P-1 Spring (a sensitive cave system discharge point); and ii) to provide preliminary information on groundwater flow conditions below a proposed timber cutting block on the west side of the GCMA (Cutblock 154-1). Detailed precipitation and water budget analysis were considered beyond the scope of the study.

The GCMA is located approximately 25 km to the south of Port McNeill on the east side of Nimpkish Lake. Most of the area is located on east- to northeast-facing slopes of the Hankin Range, and is in the upper catchment area of the Tsulton River. Small portions of the GCMA to the south and southwest are in catchment of the Noomas River. The GCMA is within the Coastal Western Hemlock biogeoclimatic zone, and has a relatively high mean annual precipitation of 100-250 cm with mean daily temperatures of less than 16°C (B.C. Ministry of Forests 1992)

The GCMA is situated on Crown land between two Tree Farm Licences (TFL s), TFL 37 of Canadian Forest Products Ltd. (CANFOR), and TFL 47 of TimberWest Forest Ltd. Most of the GCMA is crossed by a dense network of forest roads and was harvested during the mid 1980's. Numerous cave systems were discovered in the area during the late 1970's and early 1980's. Mapping and exploration of the cave systems occurred during harvesting of the area from the mid 1980's to early 1990's. A cave/karst management plan, which delineates the boundaries for the GCMA, was completed in 1995 to resolve issues between caving groups, the B.C. Ministry of Forests and forest companies (Griffiths 1994; B.C. Ministry of Forests, 1995).

The GCMA occurs near the southeastern end of a limestone belt that is part of the Quatsino Formation and is Triassic in geological age. At this location the limestone belt dips 15–30° to the east-northeast and forms the western limb of a major syncline. The axis of the syncline trends NW-SE and is located approximately 600–800 m to the east of the project area. Mafic volcanic rocks of the Karmutsen Formation conformably underlie the Quatsino Formation along the west side of the GCMA. To the east the Quatsino Formation is conformably overlain by volcanic and sedimentary rocks of the Bonanza Group. The southwest side of the area is bounded by granitic rocks of the Island Intrusives. Most of the east and southern

slopes of the area are comprised of irregular benches and depressions, with till (and/or colluvial) veneers and blankets overlying bedrock. Numerous small bedrock bluffs are present and in some cases form low north-south ridges. Steeper slopes are present along the eastern part of the area and lead down to gentle and moderate slopes to the northwest.

Significant areas of surface and subsurface karst development are present within the GCMA (Fig. 3). In total at least eight cave sites are found within the area including: Arch, Treasure, Crown Pot, P-1, Glory'Ole, Hanging Sump, Resonance, and Tsulton Rising (B.C. Ministry

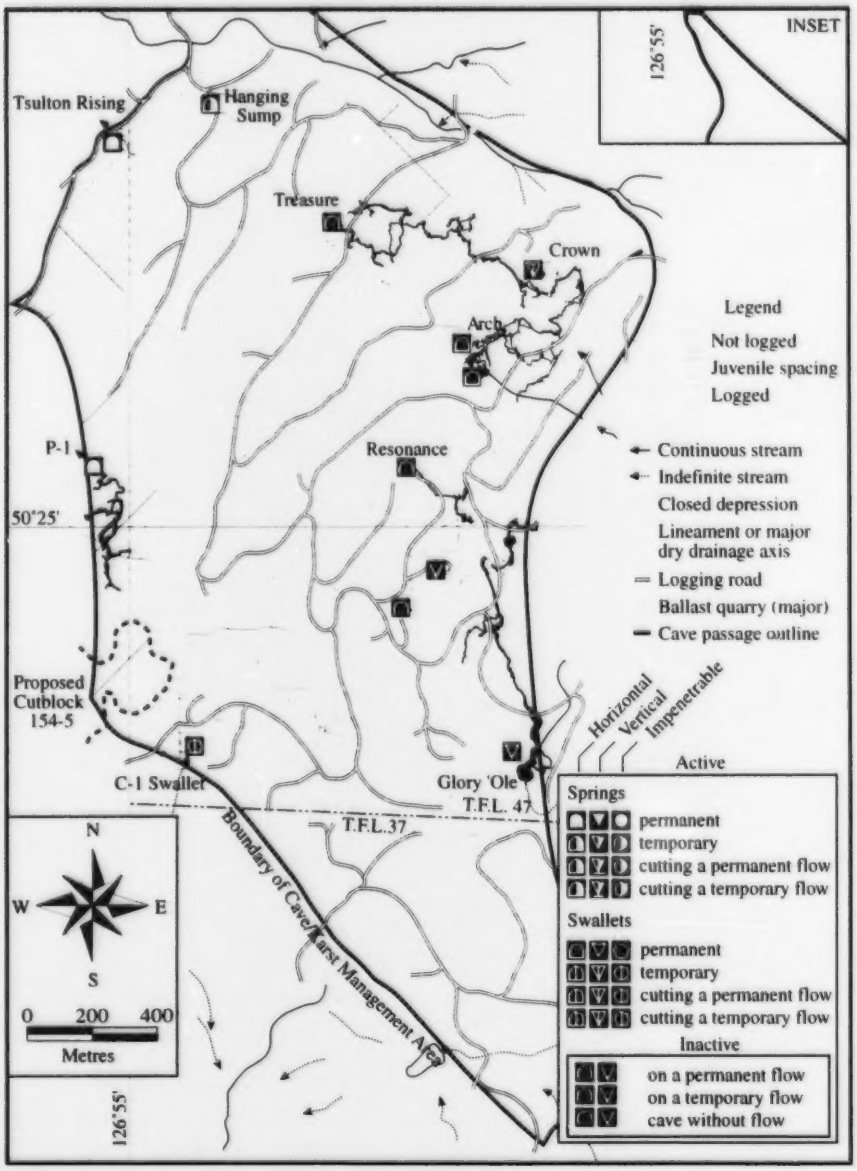


FIGURE 3 *Caves, major surface features and forestry activity.*

of Forests 1995). Most of these caves are significant in terms of their dimensions, speleothems, biota, and palaeontological content. Numerous sinkholes and depression are present throughout the area, particularly on the irregular and benched slopes. The largest sinkholes occur near the D1(Uvala) to the east and at the C-1 Swallet. The area is also crosscut by at least four dry valleys.

Streams flowing off non-karst areas onto the GCMA disappear at or near the upper limestone contact. Two of the larger streams disappear into the Glory'Ole and Arch caves. A smaller stream flows into the C-1 Swallet. Two major springs, Tsulton Rising and P-1, occur along the lower slopes of the area, while another major spring (Lunar Spring) occurs to the northwest of the GCMA. Square Corner Creek is located along the northern boundary of the GCMA and drains into the Tsulton River. The Tsulton River continues to the north along a broad valley and eventually enters the sea at Beaver Cove.

3 DYE TRACING METHODOLOGY

3.1 Design

A preliminary, office-based design for the dye tracing test was developed for the GCMA, using available topographical and geological maps, airphotos, and existing cave/karst information. A brief field reconnaissance was carried out to verify the design, and minor adjustments were made to the locations of injection and sample sites. The four injection sites chosen included: three streams along the upper limestone contact which flow into the Glory'Ole Cave, the Arch Cave and the C-1 Swallet, and a road crossing in the upper reaches of Square Corner Creek. A total of seventeen sample sites were chosen both inside and outside of the GCMA, providing as complete hydrological coverage as possible. The sample sites chosen included: known spring locations (Tsulton Rising, P-1 Spring, and Lunar Spring), seepages encountered adjacent to the main springs (e.g., Stn. #3 and #4), streams on non-karst areas nearby (e.g., Stn. #10 to #14), and the lower stream reaches some distance from the injection sites (e.g., Stn. #16 and #17). A critical part of the design was to determine which of the four dyes to place where, as all the dyes would be injected at approximately the same time. Dyes with nearly similar wavelength peaks (e.g., pyranine and fluorescein) can, in some cases, produce signatures that overlap and thus hinder interpretation. To avoid this problem, these two dyes are placed as far apart as possible, with fluorescein at Square Corner Creek and pyranine at the C-1 Swallet. Dye mobility, a function of adsorption properties onto either soil or bedrock materials, was also taken into consideration. Eosine, one of the more mobile dyes, was used at the Glory'Ole injection site, as a relatively large subsurface hydrological system was anticipated.

3.2 Implementation

The field work for the initial sampler layout and four dye injections was carried out in the early spring between March 15 and 17, 1998. At each sample location two charcoal samplers were carefully tied to either a rock or metal plate using plastic-covered steel wire. (The purpose of two charcoal samplers was to ensure that if one was lost the other would likely be recovered.) The charcoal samplers were placed into flowing water and, in places of potential high water flow, attached by a cord to a nearby tree to assist recovery. Grab water samples were taken at each location for background analysis. Sterilized plastic bottles were used, and each was labeled with the station number, date and time. At each sample and injection site the water temperature, pH and specific conductance was measured along with an estimate of flow rate. The dissolved oxygen content was measured at the three main karst springs using a portable oxygen meter and probe.

Following layout of the charcoal samplers, the four dyes were introduced at approximately the same time (within 2–3 hours) into flowing water at the injection sites. Eosine (Trace 98–01) was introduced into a stream leading into the Glory'Ole Swallet, pyranine (Trace 98–02) was introduced into a small stream draining into the C-1 Swallet, rhodamine WT (Trace 98–03) was placed into one of the streams leading into Arch Cave, and fluorescein (Trace 98–04) was placed into an upper road crossing of Square Corner Creek.

Two subsequent visits were made to the sample sites, one and two weeks following the dye injections, March 24, 1998 and April 2, 1998, respectively. The two charcoal samplers from each site were collected and placed in labeled sterile plastic bags. If one of the charcoal samplers was found in better position (e.g., one in the water flow and one out) it was preferentially chosen for analysis. Grab water samples were also taken at each site during sampler retrieval and collected in a small sterilized plastic bottle. After the first retrieval new charcoal samplers were then placed at each site, ready for the second retrieval a week later. All the charcoal samplers and grab water samples collected were sent by overnight courier to the Ozark Underground Laboratory (OUL) for analysis.

3.3 Laboratory Preparation and Analysis

The charcoal samplers and grab water samples on reaching OUL were immediately refrigerated at 4°C until time for analysis. Firstly the charcoal samplers were washed with water to removed sediment and organic debris. One of the two charcoal samplers was taken for analysis and the second was put into frozen storage. The dye was firstly removed (or eluted) from the charcoal sampler by a solution of aqua ammonia and isopropyl alcohol. The resulting solution (or elutant) that contains traces of dye materials was subjected to analysis by a Shimaddzu RF-5000 U spectrofluorophotometer under a synchronous scan protocol. Figure 4 shows examples of fluorescent peaks obtained of a background water sample and a charcoal sampler taken from Tsulton Rising. Details on all analytical data are available in Stokes (1998).

No dyes were detected in the background grab water samples that were taken during the initial sampler layout. These results were anticipated, as the area has no record of significant dye tracing, but was done as standard procedure. Findings from the four dye injections are summarized below and shown diagrammatically on Figure 5.

Eosine, injected into one of the sinking streams of the Glory'Ole Cave (Trace 98–01), was detected in all charcoal samplers from Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn.#8 (Tsulton Rising) and Stn.#17 Downstream Tsulton River. Eosine was detected in all of the first set of grab water samples, but none of the second.

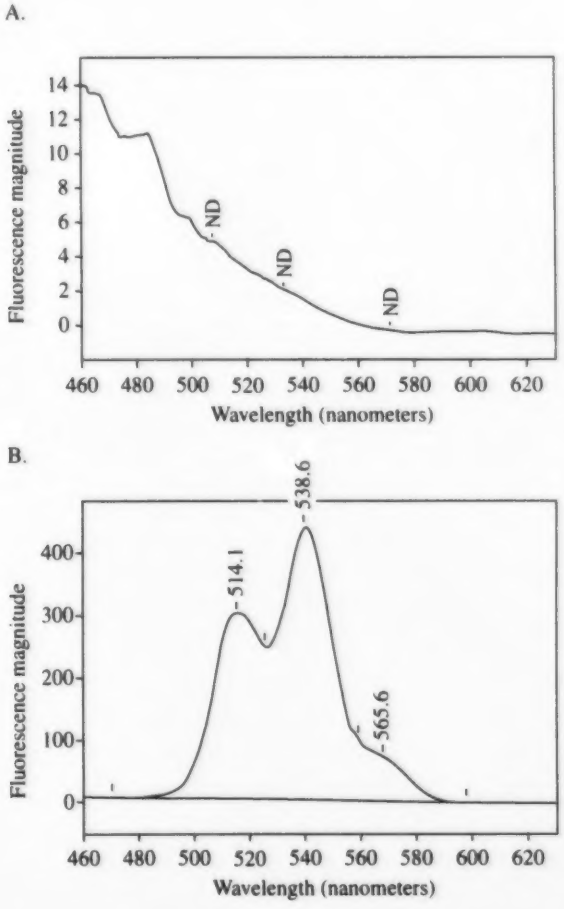
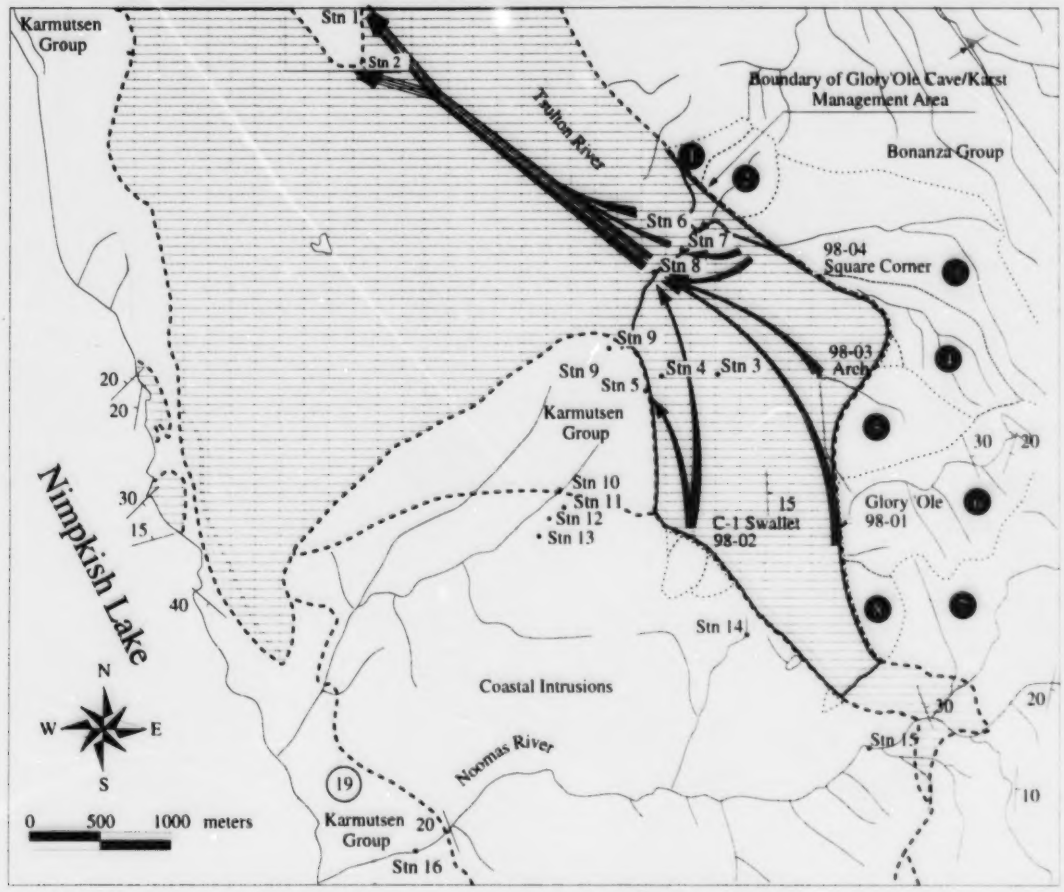
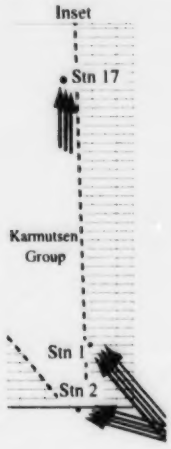


FIGURE 4 *Example of typical fluorescent spectra from dye analysis with the spectrofluorometer. A – background grab sample from Tsulton Rising (HI545) taken prior to dye injection. B – charcoal sampler from Tsulton Rising (HI875) taken one week after dye injections. Distinct peaks obtained for fluorescein (514.1), eosine (538.6) and rhodamine WT (565.6). Peak for pyranine (at 501) masked by fluorescein.*





Sample Sites	
Stn 1	Lunar Spring
Stn 2	Slot Canyon Outlet
Stn 3	Culvert Creek
Stn 4	Road End Spring
Stn 5	P-1 Spring
Stn 6	Lower Square Corner Creek
Stn 7	Below Hanging Sump Creek
Stn 8	Tsulton Rising
Stn 9	Swamp Creek
Stn 10	High Fiber Creek
Stn 11	Low Stream
Stn 12	Medium Stream
Stn 13	High Stream
Stn 14	Granite Creek
Stn 15	Upper Noomas River
Stn 16	Noomas Trestle
Stn 17	Downstream Tsulton River

Injection Sites	Trace No.
Eosine - Glory 'Ole	98-01
Pyranine - C-1 Swallet	98-02
Rhodamine WT - Arch	98-03
Fluorescein - Square Corner	98-04

Diagrammatic dye paths

Surface divides of upland karst recharge areas

Geology (from Hoadley, 1952)

Quatsino Formation

Probable contact boundaries

Synclinal axis

20 Strike/dip of bedding

FIGURE 5 *Diagrammatic groundwater flow paths and recharge areas of the Glory'Ole Cave/Karst Management Area.*

Pyranine, injected into the C-1 Swallet (Trace 98–02), was recovered from all charcoal samplers from Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn. #5 (P-1 Spring), and Stn.#8 (Tsulton Rising). Some interference in the pyranine peaks occurred due to the presence of fluorescein detected at Stns. #1, #2 and #3. This interference limited the determination of dye concentrations at these stations. Pyranine was detected in the two grab water samples taken at Stn. #5 (P-1 Spring).

Rhodamine WT, injected into the Arch Cave Tributary Stream (Trace 98–03), was recovered from all the charcoal samplers at Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn.#8 (Tsulton Rising) and Stn.#17 Downstream Tsulton River. Rhodamine WT was only detected in the first set of grab water samples from Stn. #8 and Stn.#17.

Fluorescein, injected into Square Corner Creek (Trace 98–04) was detected in all the charcoal samplers at Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn. #6 (Lower Square Corner Creek), Stn. #7 (Below Hanging Sump Creek), Stn.#8 (Tsulton Rising) and Stn.#17 (Downstream Tsulton River). Fluorescein was detected in most of the first set of grab water samples, but none of the second set.

No dyes were detected in charcoal samplers or grab water samples taken from Stn.#3 (Culvert Creek), Stn.#4 (Road End Spring), Stn.#9 (Swamp Creek), Stn.#10 (High Fiber Creek), Stn.#11 (Low Stream), Stn.#12 (Medium Stream), Stn.#13 (Low Stream), Stn. #14 (Granite Creek), Stn.#15 (Upper Noomas River), and Stn.#16 (Noomas Trestle).

Water temperature measurements taken at the sampler and injection sites varied from 0.8–6.6°C. pH readings varied from 7.4-8.6 units. Dissolved oxygen content from the three main springs indicate that the discharge waters were at or close to their saturation point with respect to oxygen. These measurements were not considered particularly useful tools for assessing these karst waters, but could indicate any abnormal conditions important for dye analysis.

The specific conductance measurements, taken at all the sample and injection sites, were more useful. (Specific conductance measures the ability of water to conduct electricity and increases with dissolved $CaCO_3$ content.) Typically, waters that occurred within or downstream from karst areas of the GCMA gave high readings, between 80–140 micromhos/cm, while waters draining non-karst areas typically gave measurements <10 micromhos/cm. This information provides a useful and inexpensive field tool for rapidly identifying karst-related waters, and can assist in the design and interpretation of dye trace studies.

5 GROUNDWATER FLOW PATHS AND RECHARGE AREAS

From the four dye traces it is apparent that the principal discharge point for subsurface flow in the GCMA is at the Tsulton Rising (Stn.#8). The dye traces, in conjunction with speleological knowledge of cave passages, suggest that the Glory'Ole, Arch and Treasure cave systems are probably hydrologically linked. Stream flows into the Glory'Ole and Arch Caves are the likely major sources of this water within the three cave systems. However, the dye trace at the C1-Swallet (Trace 98–02) also indicates a

hydrological connection with Tsulton Rising. The dye trace from Square Corner Creek (Trace 98–04) displays a subsurface hydrological link to below Hanging Sump (Stn.#7) and Tsulton Rising (Stn.#8). This subsurface flow is probably the result of an insurgent point (or points) located along the channel of Square Corner Creek below the injection site at Trace 98–04. This emphasizes the point that surface creeks adjacent to, or crossing, karst areas can lose (or conversely gain) water flow along their length, and that these creeks warrant dye tracing along with sinking streams.

A subsurface hydrological link was also confirmed between the C1-Swallet and the P-1 Spring (Stn.#5) from Trace 98–02. However, there was some imbalance in the apparent flow rates between the C-1 Swallet and the P-1 Spring, with relatively small flows in the C-1 Swallet as compared to the P-1 Spring. This suggests that subsurface water for the P-1 Spring probably comes from other sources as well. Possible sources include the disappearing streams that occur to the south of the Glory'Ole Cave and/or the dry valley southeast of the P-1 Spring. The area extent of this dry valley appears sufficient for recharge of the P-1 Spring by precipitation alone.

All four dyes were detected at Slot Canyon (Stn.#2) and at Lunar Spring (Stn.#1). From the dye concentrations obtained it was apparent that greater amounts of fluorescein (and corresponding low amounts of eosine and rhodamine WT) were detected in the samplers from Lunar Spring (Stn.# 1) as compared to Tsulton Rising (Stn.#8). This suggests that most of the flow of Lunar Spring is probably derived from Square Corner Creek, and that at some point (or points) between Tsulton Rising (Stn.#8) and Slot Canyon (Stn.#2) water flow is probably redirected subsurface towards the Lunar Spring (Stn.#1). From this information it is apparent that successful dye tracing requires looking outside the area of specific interest to ensure that the full extent of the karst hydrological system is investigated.

Fluorescein, eosine and rhodamine WT were all detected at Downstream Tsulton River (Stn.#17) which is approximately 7-8 km from the injection sites. This shows the good mobility of these three dyes, which can travel significant distances without major losses onto organics, soil or rock. From this result it is apparent that sample sites could be located a significant distance away from injection sites, and could be particularly useful where access to areas is limited. Pyranine was not detected at Downstream Tsulton River (Stn.#17), but did however reach Slot Canyon (Stn.#2). Pyranine was also not detected as might have been anticipated below the P-1 Spring (Stn.#5) at Swamp Creek (Stn.#9). This might be a function of pyranine's tendency to be more readily adsorbed onto organic materials and vegetation as compared to the other dyes. Out of the four dyes used pyranine is probably the least preferred.

No dye was detected in the samplers along Noomas drainage to the south (Stns.#14, #15 and #16) and the other creek system to the southwest of the area (Stns.#10, #11, #12 and #13). This confirms that none of the four dye injection sites within the GCMA is hydrologically linked to these water courses. These data are compatible with the low specific conductance readings taken at these locations and suggests limited contact of the water with limestone.

The lack of dyes detected at Culvert Creek (Stn.#3) and Road End Spring (Stn.#4) indicate that these water flows are not connected to any of the injection sites. These sites of water flow are both probably expressions of discharge from localized catchment areas upslope (e.g., small gullies or draws).

Recharge catchment areas on non-karst terrain occur upslope of the GCMA and contribute water to sinking streams that enter the karst groundwater system. This water eventually discharges at springs a significant distance away from the recharge areas. The topographic divides for each of these non-karst recharge catchment areas upslope has been delineated on Figure 5. Recharge Areas 6 and 5 occur immediately upslope of the injection sites of the Glory'Ole Cave (Trace 98-01) and Arch Cave (Trace 98–03), respectively, and both contribute to the groundwater systems that discharges at Tsulton Rising. The recharge areas of Square Corner Creek, and its tributary to the north (Areas 4 and 3, respectively) also contribute to discharge at Tsulton Rising. A small recharge area contributes to the C1-Swallet and is shared between the P-1 Spring and Tsulton Rising. Recharge areas for the Tsulton Rising and P-1 Spring within the GCMA itself are difficult to determine without site-specific dye tracing of water input sites.

In summary, the dye tracing results indicate relatively rapid response times occur between the insurgent and exsurgent points of the groundwater system within the GCMA. In all likelihood turbulent water flows could develop in this type of groundwater system, which would be capable of transporting significant amounts of sediment and debris. The results obtained are considered consistent with the recovery of all the dyes from the four traces. No significant undetected losses outside of the project area were anticipated.

6 IMPLICATIONS FOR FOREST MANAGEMENT

Dye tracing provides an important insight into the groundwater systems of karst terrain and can have significant implications for forest management. One of the principal concerns during the forestry activities of harvesting or road construction is the changes to terrain conditions and hydrology, which can have significant impacts on water quality and quantity. In non-karst areas most of the water flow occurs as surface overland flow which collects along road ditches, and originates from intersected streams and seepages. Typically, in non-karst areas there is some potential for attenuation of the surface overland flow between the area of activity and downstream resources (e.g., vegetation along banks of streams catching sediment). In karst terrain water flow rapidly enters natural openings on the surface (e.g., swallets, sinkholes, epikarst) and drains vertically into subsurface conduits. Water and any entrained materials (e.g., sediment, logging debris and contaminants) can be transported a considerable distances downstream with little to no attenuation. These "piped" materials can cause detrimental impacts to a variety of instream and downstream resources, such as fisheries or community water supplies. Changes in peak flows or flow direction (by

harvesting or road construction) can alter the volumes of water entering into subsurface conduits and result in subsurface flooding or drying, and variations to spring discharge rates.

Some preliminary information on the subsurface hydrological conditions below Cutblock 154-5 can be inferred from the dye tracing and available geological maps. The lower slopes of the cutblock appear to have no karst hydrological concerns, as they are underlain by granitic bedrock and drain away from the limestone contact. The upper part of the cutblock is underlain by limestone and is located midway between the C-1 Swallet and the P-1 Spring. In this area further dye tracing would be required to determine its hydrological significance, as it is potentially in the recharge area of the P-1 Spring. A "dry set" dye introduction could be carried to confirm this. (A dry set is where dye is placed in such a manner as to be taken into solution by the first surface flow reaching the site.)

Qualitative sensitivity ratings for non-karst recharge can be determined once the karst groundwater flow paths are known and the downstream resources evaluated. For example, the non-karst recharge catchment areas immediately upslope of the Glory'Ole Cave, Arch Cave, Square Corner Creek and its northern tributary (Areas 3, 4, 5 and 6) all contribute water flow to the Tsulton Rising. These four areas could therefore be considered more hydrologically sensitive than Areas 1, 2, 7 and 8. This application of dye tracing information can be used as a guide for responsible forest management. Forestry activities in the more sensitive areas might require limitations on the size, number and shape of cutblocks; the location and density of roads; and the harvesting methods (e.g., heli-logging, ground-based or cable systems). Special prescriptions may be required for sensitive creeks (e.g., sinking streams), with the development of riparian reserves and the careful construction of road crossings. At present some forest companies are using variable retention as a method of harvesting, as opposed to larger clearcuts. This approach might be suitable for sensitive recharge areas.

7 CONCLUSIONS

1. The dye tracing project at the GCMA has demonstrated that a significant amount of information can be obtained about non-karst recharge and karst groundwater flow paths. Dye tracing appears a useful tool for investigating groundwater issues related to forest management in karst areas, particularly where activities might have any impact on water quality or quantity.
2. All four dyes were detected at Tsulton Rising, the principal discharge point for subsurface flow in the GCMA stream flow into the Glory'Ole and Arch Caves and along Square Corner Creek are probably the major sources of this water. Dye from the C1-Swallet indicates a subsurface hydrological link to the P-1 Spring.
3. All four dyes were detected at Slot Canyon (Stn.#2) and at Lunar Spring (Stn.#1). From the dye concentrations it is apparent that most of the flow of Lunar Spring is derived from Square Corner Creek, and is probably the result of an insurgent point (or points) along the channel.

4. Fluorescein, eosine and rhodamine WT were detected 7-8 km below the injection sites at Downstream Tsulton River (Stn.#17), indicating the good mobility characteristics of these dyes.
5. Non-karst recharge catchment areas upslope of the Glory'Ole Cave, Arch Cave, Square Corner Creek and its northern tributary all contribute to the groundwater systems that discharge at Tsulton Rising. These recharge areas are considered hydrologically sensitive to disturbance by forestry activities, and site-specific prescriptions are required for careful forest management (e.g., riparian reserves).
6. In terms of completing future dye tracing projects in similar forest karst areas it is recommended that: i) professional direction be used for their design and implementation, ii) fluorescein, eosine and rhodamine WT be used in preference to pyranine, iii) specific conductance measurements be taken, and iv) streams adjacent to and crossing the karst areas be considered, along with sinking streams, as potential dye injection sites.

8 ACKNOWLEDGEMENTS

Acknowledgement should be given to the two licensees, TimberWest Forest Ltd. and Canadian Forest Products Ltd., for showing their interest in the project. Special thanks should be given to Cam Brady of the Port McNeill Forest District for funding and initiating the project.

9 REFERENCES

Aley, T. and Aley, C. 1993. Delineation and hazard area mapping of areas contributing water to significant caves. Proceedings of the 1993 American Cave Conservation Association. 116–122.

Baichtal, J.F. In press. Application of a karst managment strategy: Two cases studies from the Tongass National Forest, southeastern Alaska. The challenges of implementation. *In* Proceedings of the 1997 Karst and Cave Management Symposium, Bellingham, Washington, USA.

Baichtal, J.F. and Swanston, D.N. 1996. Karst landscape and associated resources: A resource assessment. General Technical Report PNW-GTR-383. USDA Forest Service. Pacific Northwest Research Station, Portland, Oregon.

B.C. Ministry of Forests. 1992. Biogeoclimatic zones of British Columbia. 1:2,000,000 map. Research Branch.

B.C. Ministry of Forests. 1994. Cave/karst management handbook for the Vancouver Forest Region.

B.C. Ministry of Forests. 1995. Glory'Ole Area Cave/Karst management plan. Prepared by the Port McNeill Forest District.

B.C. Ministry of Forests. 1997. A complex landscape sculpted by water. Information brochure from the Forest Practices Branch.

Cooke, R.U. and Doornkamp, J.C. 1990. Geomorphology in environmental management. Clarendon Press, Oxford.

Doerfliger, N. 1996. Advances in karst groundwater protection strategy using artificial tracer test analysis and multi-attribute vulnerability mapping (EPIK Method). Unpublished PhD Thesis. Neuchatel University, Switzerland.

Field, M.S., Wilhelm, R.G., Quinlan, G.F. and Aley, T. 1995. An assessment of the potential adverse properties of fluorescent tracer dyes used for groundwater tracing. Environmental Monitoring and Assessment 38(1):75–96.

Fischl, P. 1992. Limestone and dolomite resources of British Columbia. B.C. Geological Survey Open File 1992–18.

Ford, D.C. and P. W. Williams. 1989. Karst geomorphology and hydrology. Unwin Hyman Ltd., London, U.K.

Griffiths, P. 1991. A resource user's perspective on cave management. British Columbia Caver 5(3):16–20.

Griffiths, P. 1994. Cave/karst mapping for the Glory'Ole Area management plan. Unpublished report completed by Cave Management Services for Port McNeill Forest District.

Kiernan, K. 1990. Soil and water degradation in carbonate rock terrains. Australian Journal of Soil and Water Conservation 3(4):26–33.

Smart, P.L. 1984. A review of the toxicity of twelve flourescent dyes used for water tracing. The National Speoloelogical Society Bulletin 46: 21–22.

Stokes, T.R. 1998. Regional dye tracing project for the Glory'Ole Cave/ Karst Management Area, Nimpkish Lake, B.C. Unpublished report completed for the Port McNeill Forest District, B.C. Ministry of Forests.

Stokes, T.R. 1996. A preliminary problem analysis of cave/karst issues related to forestry activities on Vancouver Island. Unpublished report completed by Terra Firma Geoscience Services for Vancouver Forest Region, B.C. Ministry of Forests.

U.S. Forest Service, 1995. Final karst vulnerability assessment report, Phase II site-specific verification study, Lab Bay Environmental Impact Statement, Prince of Wales Island, Alaska. Prepared by Harza Northwest, Inc. and Ozark Underground Laboratory for the USDA, Tongass National Forest, Ketchikan Area, Thorne Bay Ranger District.

White, W.B., Culver, D.C., Herman, J.S., Kane, T.C. and Mylroie, J.E. 1995. Karst lands. American Scientist 83: 450–459.

APPENDIX 2 Classification system for discrete mesoscale and microscale surface karst features

Taken from *Part A of Method for Managing Discrete Surface Karst Features*, Cave Management Services, Campbell River, British Columbia, 1993 (Unpublished).

GENERAL

The evaluation criteria include dimensional characteristics, function (e.g., hydrology), actual or potential resource values, and "intangibles" such as the visual quality of the individual feature. These criteria require varying degrees of subjectivity and judgement.

The subset criteria presented are not necessarily applicable to all features. For example, hydraulic characteristics such as sinking stream incisement or catchment size are not applicable to microscale surface karst features such as grikes or karren. Nor are the criteria listed in the order of importance that is applicable to all features.

The criteria may change with time as new values evolve, or as the number of remaining undisturbed or "pristine" features diminishes.

Timing

The significance of surface karst features is determined prior to road-building and harvesting plan preparation, and after an acceptable level of ground searching. Until this evaluation takes place the features are regarded as "potentially significant" and managed accordingly. Neither roadbuilding nor harvesting is approved during this interim period.

METHODOLOGY

The highest numerical ranking (1 through 3) *for any one value* determines the significance of the feature. For example, based on volume only, a doline is a significant feature (i.e., Type 3), without any further evaluation.

(Refer to Figure 1 for classification flow.)

The sum of numerical rankings for each value can be used in a matrix table for comparison between two or more features.

CRITERIA

Dimensional Characteristics

Widths, lengths, and depths are readily determined for closed depressions. Sinkhole and doline diameters are measured and ranked accordingly. It should be possible to generate and maintain a database of the largest dolines on Vancouver Island.

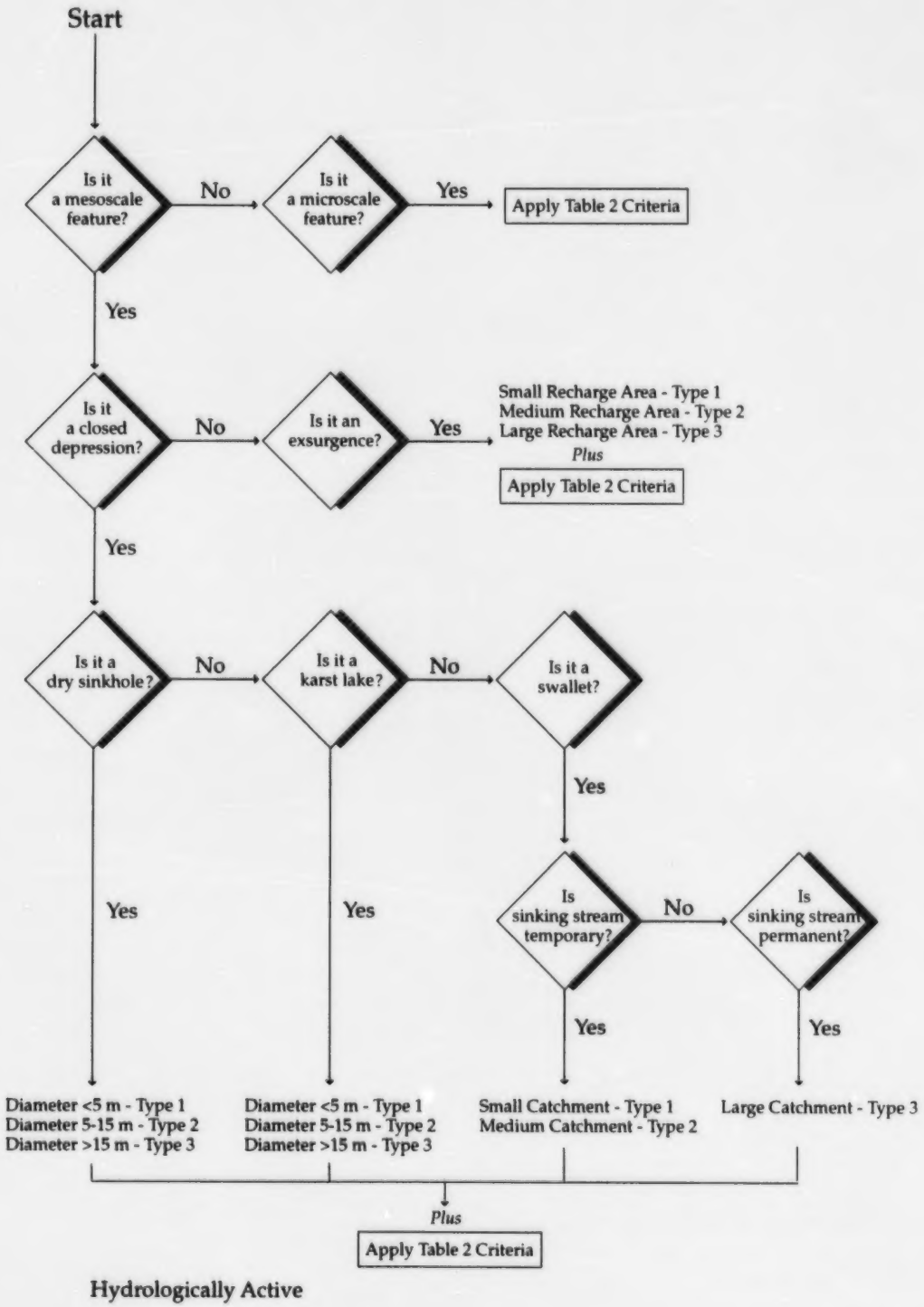


FIGURE 1 *Classification flow for discrete surface karst features.*

HYDROLOGY

Karst Lakes and Ponds

The size of the enclosed body of standing water is the principal determinant of significance. Symmetry and depth of water are also considered where appropriate.

Swallets

The catchment of a sinking stream is considered in determining the significance of a swallet. Swallets with intermittent or ephemeral (i.e., temporary) sinking streams are less significant than those with permanent streams. Permanent sinking streams with catchments exceeding 100 ha are most significant. Catchment size is estimated from contour mapping, field checking, or influent channel morphology. Beds of permanent sinking streams with large catchments show evidence of flowing water, a gravel, pebble, rocky, or sandy bed, an obvious gully, or short steep banks. Sinking streams that are known to resurge as productive surface streams or as domestic water supplies are also significant. Sinking streams suspected to contribute to productive surface waters or domestic water supplies will be managed as Type 3, until proven otherwise by dye tracing or other appropriate methods.

Exsurgences

More difficult to assess is the recharge area of exsurgences. The exsurgent channel morphology can provide some information, but the knowledge obtained from underground exploration and dye tracing is more precise. Exsurgences that rise as productive surface streams or domestic water supplies are significant.

GEOLOGY

The uniqueness of the geological setting is established from field identification of the host carbonate bedrock. Features that are found in uncommon geological strata are the most significant.

BIOLOGY

The assessment of the biological value (e.g., biodiversity) of a feature may necessitate evaluation by taxonomists and other specialists. The utilization of the feature as habitat for wildlife would involve other disciplines. The presence of rare or endangered flora or fauna is a significant value. In particular, the ability of refugial biota to recolonize other features, should a disturbance occur, is an important consideration. The presence of elevational gradients of biota, such as occur in large closed depressions, is of high significance. Unique or rare habitats for large mammals and fur-bearers and water sources for the same are significant.

Ecological Zones

The ecological classification of a surface karst feature is determined from the published biogeoclimatic mapping. The abundance of the feature in the particular ecological zone is checked against the database. The presence of a surface karst feature within a karst ecosystem that is poorly represented within a particular ecological zone is of special interest.

ARCHAEOLOGY

Determining the significance or potential archaeological significance of a surface karst feature may require archival research or archaeological surveys. This normally requires cultural heritage expertise.

HISTORICAL OR CULTURAL VALUES

The determination of the historical or cultural values of a surface karst feature may require consultation with local inhabitants, including native groups, and the B.C. Heritage Conservation Branch. Features that are presently recognized by the general public or the caving community as having value are most significant.

TABLE 1 *Classification system checklist for closed depressions and exsurgences*

Dimensional Characteristics – Closed Depressions

	Type 1 ▼	Type 2 ▼	Type 3 ▼
	Sinkholes (dry)		Dolines (dry)
Diameter at rim	❑ *<5 m*	❑ *5-15 m*	❑ *>15 m*
	Karst Ponds		Karst Lakes
Diameter of enclosed body of standing water	❑ *<5 m*	❑ *5-15 m*	❑ *>15 m*

Hydrology – Swallets

	Type 1 ▼	Type 2 ▼	Type 3 ▼
	Sinkhole		Doline
Sinking stream type	*temporary*		*Permanent*
Catchment size	❑ *small*	❑ *medium*	❑ *large*[1]

Exsurgences

	Type 1 ▼	Type 2 ▼	Type 3 ▼
Recharge area	❑ *small*	❑ *medium*	❑ *large*

[1]large sinking stream catchment size (>100 ha) or multiple sinking streams

SCIENTIFIC, EDUCATIONAL, OR RECREATIONAL VALUES

The assessment of the scientific, educational, or recreational value of a surface karst feature can extend beyond the consideration of contemporary benefit or use, and accessibility. The *potential* future use of a feature (e.g., interpretative karst viewing) is considered. Paleontological features are of significant scientific and educational value.

COMMERCIAL VALUE

Surface karst features may provide significant opportunities for commercial tourism. Exsurgences may have significant present or future value for commercial spring or mineral water production.

VISUAL QUALITY

The pristine character of the surface karst feature is significant. The association of certain features with an advanced stage of natural forest growth, such as climax forest, is usually of the highest visual value.

ABUNDANCE

The abundance criterion is applied to the individual feature, but it is equally applicable for determination of significance of an individual feature, or cluster of features, at a local, regional, national, or international level.

CONNECTIVITY

The connectivity between the feature and other significant surface karst features or caves within the same karst ecosystem contributes to the significance of the feature.

TABLE 2 *Classification system checklist for all discrete mesoscale and microscale surface karst features*

	Type 1 ▼	Type 2 ▼	Type 3 ▼
Geology	❑ common	❑ uncommon	❑ unique or rare
Biology	❑ low	❑ moderate	❑ high
Archaeology	❑ low	❑ moderate	❑ high
Historical or Cultural	❑ low	❑ moderate	❑ high
Scientific, Educational, or Recreational	❑ low	❑ moderate	❑ high
Commercial	❑ low	❑ moderate	❑ high
Visual Quality	❑ low	❑ moderate	❑ high
Abundance	❑ common	❑ uncommon	❑ unique or rare
Connectivity	❑ low	❑ moderate	❑ high